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Abstract

The overall aim of this research is to gain insight into the etiology of tibial stress fractures. Three dimensional motion analysis data along with structural data will be collected from 400 subjects (200 at each site) over a 3-year period. 30 of the subjects will have sustained a tibial stress fracture prior to the study and the other 370 will have not. Subjects will be recruited primarily from track teams, running clubs, and physicians local to the University of Delaware and University of Massachusetts. Within this Annual Report, information concerning adherence to work objectives, preliminary results with respect to the proposed hypotheses, and reportable outcomes are presented for the third year of the investigation. Overall, we have adhered to most work objectives and have proposed plans for rectifying any discrepancies. The preliminary analysis of the data demonstrates encouraging results and support of most hypotheses.

Table of Contents

Cover.....	
SF 298.....	
Table of Contents.....	
Introduction.....	5
Body.....	5
Key Research Accomplishments.....	11
Reportable Outcomes.....	12
Conclusions.....	44
References.....	46
Appendices.....	48

INTRODUCTION

Stress fractures can be extremely costly to the military in terms of both time and medical expenses. The tibia is a common site for such injuries and has been most often associated with running, an activity common to all military training. Stress fractures are among the top 5 cited lower extremity injuries sustained by runners (Clement et al., 1981; Kowal, 1980; James et al., 1978; Jones, 1983; Pagliano and Jackson, 1980; Reinker and Ozburne, 1979). They are among the most serious of running-related overuse injuries as they take long to heal and if untreated, can progress to a macrofracture. Females are a growing military contingency and appear to be particularly susceptible, as it has been noted that they are twice as likely to experience a stress fracture as their male counterparts (Brudvig et al, 1983; Pester and Smith, 1992; Reinker and Ozburne, 1979).

Structural and biomechanical factors have been suggested in the cause of stress fractures. However, these mechanisms are not well understood. Therefore, the purposes of this study are 1) to compare the structure and mechanics of runners who have sustained a tibial stress fracture to those who have not, 2) to gain an understanding of which combination of factors (structural and/or biomechanical) are predictive of tibial stress fractures, and 3) to assess whether mechanics are altered following a tibial stress fracture. Once the factors associated with stress fractures are identified, future work will focus on formation and testing of a simple screening tool to facilitate identification of those at risk.

This is a dual-site investigation (University of Delaware & University of Massachusetts, Amherst) which began on September 1, 2000 and has been under investigation for five years. This Annual Report will focus on results after the fifth year of the study. We have been granted a no-cost one year extension, making this the penultimate year of the study.

BODY

Summary of Methodology

The overall aim of this research is to gain insight into the etiology of tibial stress fractures. Three dimensional motion analysis data along with structural data will be collected from 400 subjects (200 at each site) over a 3-year period. A minimum of 30 subjects will have sustained a tibial stress fracture prior to the study. Subjects will be recruited primarily from track teams, running clubs, and physicians local to the University of Delaware and University of Massachusetts. All subjects will be females between the ages of 18 and 45 and will be free of lower extremity injury at the time of testing. Lower extremity kinematics and kinetics will be collected during running. In addition, radiographs of both tibiae will be taken as well as clinical measures of lower extremity alignment. Subjects will then report their exposure data (mileage, intensity, terrain) as well as any injuries they have sustained each month via a custom developed webpage which will serve as a database for this information. If a subject reports a tibial stress fracture/reaction, the site coordinator will be notified automatically and the subject will be asked to return for a second running analysis once the fracture has healed and they are cleared to run by their physician. The structural and biomechanical factors leading up to a tibial stress fracture will be assessed. In addition, comparisons will be made of mechanics before and after the stress fracture to determine whether subjects revert to

their pre-injury mechanics. If relationships between mechanics and injury are established, future interventions including gait retraining should be explored.

Statement of Work

Between the two data collection sites, the following objectives were outlined in the approved Statement of Work for the fifth year. These objectives included:

1. Recruitment of additional subjects to assist in capturing more tibial stress fractures (Added following low number of tibial stress fractures recorded by end of year 4)
2. Complete data collection and reduction on any subjects who have sustained a fracture
3. Complete follow-ups
4. Re-collect data on control group of subjects, who did not sustain a fracture
5. Complete predictive model based on all subjects who sustained a tibial stress fracture during the course of the study
6. Complete analysis of post-fracture data to determine whether the injury resulted in a change in mechanics
7. Two manuscripts submitted: one regarding predictive model of tibial stress fractures, second regarding influence of tibial stress fracture on mechanics.

Adherence to Work Objectives

1) Recruitment of Subjects

To date, data have been collected on a total of 414 subjects: 214 at the University of Delaware and 200 at the University of Massachusetts. Although the initial target of 400 runners enrolled into the study has been met, we will continue to recruit runners into the study for an additional year to increase the likelihood of more prospective stress fractures occurring during the study. In addition, this will allow us to continue to follow up with those added in the 4th and 5th year of the study.

As with all prospective studies, the exact number of injuries that will occur in the study sample is unknown. The reported incidence of stress fractures ranges from 1-25% (Bensel et al., 1983; Brudvig et al., 1983; Kowal, 1980; McBryde et al., 1981; Milgrom et al., 1989; Reinker et al., 1979; Zernicke et al., 1993). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (Pester & Smith, 1992). We based our power calculations on a 5% incidence rate. Therefore, given 400 subjects, we expected 20 fractures. To date, we only have 6 prospective tibial stress fractures. We are hopeful that continuing to recruit runners in the higher risk, 18 to 30 years age group during the one year no-cost extension will facilitate capture of more tibial stress fractures.

2) Collection of Data on those who have sustained a stress fracture

The data from the tibial stress fracture group prospectively are included in the Reportable Outcomes section in a comparison with a matched control group of subjects who have not sustained a fracture. Due to the low number of tibial stress fractures or reactions that have occurred during the study so far, we have also included a comparison of all subjects who have sustained a lower extremity stress fracture (pelvis and distally) to a matched control group

To date, eight tibial stress fractures in six individuals have been recorded prospectively. Based on a study by Frederickson et al (1995), we have considered a tibial stress reaction to be the early stages of a stress fracture. In the grant, we operationally defined a tibial stress reaction as pain located along a diffuse area of the tibia (and not in the muscle compartments) that worsens with running and is relieved with rest. Some runners will discontinue or reduce their running in response to diffuse tibial pain. However, we proposed exploring their mechanics, as well, as we believed that these data will help lend insight into the etiology of tibial stress fractures. To date, we have recorded 12 tibial stress reactions in 7 individuals. Following comments made by the reviewer of last year's report, we have not pooled these data with tibial stress fractures. Results from these analyses are presented separately in the Reportable Outcomes section.

3) Follow-ups

Subjects have been tracking their monthly running exposure and injuries since their initial visit and these data have been input into the database. The database continues to function properly and subjects have been logging in on a monthly basis to record their mileage and injuries. A summary of the injuries reported has been summarized in the Reportable Outcomes section.

255 subjects have now completed their participation in the study, including their two year follow up. 149 subjects from the University of Delaware have completed, and 106 at the University of Massachusetts.

The compliance rate for subjects who continue to report mileage and injuries for the follow up part of the study is high, and stands currently at 91%, an improvement on the 86% compliance rate reported last year and 80% the year before that. This is a positive result, since more subjects have now been enrolled in the study for a longer time, providing greater opportunity for attrition. Dropouts are defined as a subject not having entered a monthly report into the website for 12 or more consecutive months. Subjects who have not responded to the monthly email request for their running data for a shorter period are contacted by telephone to obtain backdated monthly information. This method seems to have been successful. To date, a total of 83 subjects have dropped out of the study. In addition, 16 subjects that have stopped running for various reasons have withdrawn from the study. This has resulted in an overall attrition rate of 24%. This is acceptable for a follow up study of this long duration with such a large number of subjects enrolled, and is not a cause for concern.

Currently, compliance rate is calculated as the number of monthly responses submitted by a subject being divided by the number of monthly requests for data. Additional entries that were received from some of the early recruits to the project, backdating their records to the months before the website was online, are not included. Furthermore, any erroneous double submissions of the same data were excluded from the total number of submitted entries for an individual. We believe these measures have resulted in an accurate indication of compliance rate during follow-up.

Previously, the reviewers of the Annual Report have suggested that the self-report injury information collection forms on the website may contain items that are hard for the participants to judge due to anatomical and medical terms being used. If self diagnosed initially, subjects are encouraged to report their injuries after they have been diagnosed by a medical professional. To date, only 127 of 919 (14%) of prospective injuries reported to date were diagnosed by someone other than a medical professional. This is the same as last year when 104 of 747 (14%) prospective injuries reported to date were diagnosed or treated by someone other than a medical professional and represents a consistent improvement on the year before last when 53 of 226 (23%) injuries were self-reported. We believe this maintained improvement is due to following up self-reported injuries by email to determine whether a medical professional was consulted at any time for the injury.

Subjects are encouraged to contact us if there is a question regarding their injury. They are also provided a space for comment on the online form regarding their injury. When any injuries related to the anterior lower leg are reported a clinician on the project has followed up with a telephone call. Therefore, we are able to further confirm the diagnosis. Any reported tibial stress fractures must be confirmed by x-rays, bone scans or MRIs. Tibial stress reactions have been operationally defined as bony pain specifically along the distribution of the tibia that is worsened with impact loading and relieved with rest. There is indication in the literature (Fredericson et al., 1995) that these stress reactions are the early stage of a stress fracture.

4) Control group of uninjured subjects

Data from seven subjects who did not sustain any injury during at least 12 months of follow-up has been collected. These runners will serve as the control when assessing changes in mechanics following a stress fracture. We intend to continue to collect data from uninjured subjects for the control group during the no-cost extension. These data will be included in the final report.

5) Predictive model based on the data of subjects who have fractured during the course of the study to date

Due to the lower than expected occurrence of tibial stress fractures in subjects enrolled in the study, we have focused our predictive model on the retrospective tibial stress fracture data. We hypothesized that the magnitude of tibial shock would discriminate between runners with and without a history of tibial stress fracture, since preliminary results

indicated that this variable was consistently higher in runners with tibial stress fracture. A binary logistic regression was carried out to determine whether PPA predicted group membership.

The results of the binary logistic regression suggested that increased tibial shock is related to an increased likelihood of being in the RTSF group. The model indicated that for every 1g increase in PPA, the likelihood of having a history of TSF increased by a factor of 1.361 (95% confidence interval 1.020 to 1.816, $p = 0.036$). According to the model chi-square statistic, the model is significant ($p = 0.020$). It also predicted group membership correctly in 70% of cases. The Nagelkerke R square value is 0.169, suggesting that 17% of the variance between the two groups was explained by PPA. These results are detailed in a manuscript that is currently under review.

6) Analysis of pre-post fracture mechanics

To date, six runners with 8 tibial stress fractures have been recorded prospectively. All of these have now returned to the laboratory for a post-injury gait reassessment. These data are presented in the Reportable Outcomes section. In addition, the data from the tibial stress fracture group prospectively are also included in the Reportable Outcomes section in a comparison with a matched control group of subjects who have not sustained a fracture. Due to the low number of tibial stress fractures that have occurred during the study so far, we have also included a comparison of all subjects (28 fractures in 20 individuals) who have sustained a lower extremity stress fracture (pelvis and distally) pre and post-injury and to a matched control group.

7) Abstract and manuscript submission

Manuscript Submission

Three articles have been submitted to peer-reviewed journals for publication and are currently under review.. The first of these is titled "Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners", submitted to *Medicine and Science in Sport and Exercise*. The second article was developed from an abstract presented at the American College of Sports Medicine Annual Meeting in 2004 and is titled "Free moment as a predictor of stress fracture in distance runners". It was submitted to the *Journal of Biomechanics*. The third article is titled "Prospective Biomechanical Investigation of Iliotibial Band Syndrome in Competitive Female Runners", submitted to *American Journal of Sports Medicine*. These articles are included in Appendix A.

A number of other manuscripts are planned for the next year including one on prospective stress fractures as well as other injuries of high prevalence, including plantar fasciitis and patellofemoral pain syndrome. In addition, the variables that appear to be most elevated in runners who develop stress fractures occur in approximately the first 50 ms of stance (peak shock and loading rates). Therefore, we have begun to assess other variables, such as knee flexion excursion and knee stiffness, during this initial loading period. We plan on submitting an abstract relating to this to the American College of Sports Medicine and a manuscript to *Medicine and Science in Sport and Exercise*.

Abstract Submission

In the past year, six additional abstracts have been submitted and were accepted for presentation. Three abstracts were presented at the American College of Sports Medicine National Meeting in Nashville, Tennessee and three were presented at the International Society of Biomechanics/ American Society of Biomechanics Combined Meeting in Cleveland, Ohio in August 2005. The references are provided in the Reportable Outcomes section and the complete abstracts are included in Appendix B. In addition, one abstract was presented at the Center for Biomedical Engineering Research Symposium held at the University of Delaware.

KEY RESEARCH ACCOMPLISHMENTS

- Three articles have been submitted to peer-reviewed journals about the relationships between history of tibial stress fracture and differences in kinematic, kinetic and structural variables and the mechanics associated with iliotibial band syndrome.
- To date, 12 abstracts that have been presented at various national and international conferences about the incidence of lower extremity stress fractures and their relationship to kinematic, kinetic and structural variables, the main thrust of the study.
- Additionally, a further seven abstracts concerning the relationships between lower extremity mechanics and three common running injuries: iliotibial band friction syndrome, plantar fasciitis and patellofemoral pain syndrome have been presented.
- The main focus of this study is the elucidation of the relationships between lower extremity structure, mechanics and the occurrence of tibial stress fractures. However, the large database of biomechanical, training and injury data that is being compiled during the study is proving to be a valuable source of retrospective and prospective information relating to other running injuries.
- At completion, the database generated from the 400-plus runners enrolled into this study will be a very comprehensive record of the biomechanics of female runners, their injury history and prospective injuries over a two year period. This will prove to be an invaluable resource not only in relation to stress fractures, but the many other running injuries that are common and result in time lost from training for both civilians and military recruits.

REPORTABLE OUTCOMES

This section contains all of the Reportable Outcomes to date:

- 1) Retrospective tibial stress fracture data (n=24) used as basis for the manuscript that was submitted
- 2) A summary of the prospective tibial stress fracture data (eight fractures in six individuals)
- 3) A summary of all the lower extremity prospective stress fracture data
- 4) A summary of the pre and post injury data from the eight prospective tibial stress fractures in six individuals that have returned for a second assessment following recovery from injury
- 5) A summary of the pre and post injury data from the 28 prospective lower extremity stress fractures in 20 individuals that have returned for a second assessment following recovery from injury
- 6) A summary of the initial and revisit data from seven control subjects
- 7) Details of the abstracts presented based on data collected during this study
- 8) Other presentations made
- 9) A summary of the information recorded in the database.
- 10) A summary of degrees obtained that are supported by this award
- 11) A summary of employment and research opportunities applied for and received based on experience and training supported by this award

1) Summary of data on female runners who had sustained a tibial stress fracture previously

Aim 1: Determine whether differences in structure and mechanics exist between subjects with a prior tibial stress fracture to those who have not sustained a fracture.

At present, we have data for retrospective tibial stress fractures have been reported in 24 subjects. This group (RTSF) was matched with 24 control subjects (CON), who have never sustained any stress fractures, to enable assessment of the lower extremity structural and biomechanical differences between the two groups. The groups were matched for monthly running mileage and age, to remove the influence of these potentially confounding factors (Table 1).

Table 1: Mean (\pm standard deviation) monthly running mileage and age of the TSF and CON groups

	Mileage (miles/ month)	Age (years)
TSF (n=24)	121 \pm 46	29 \pm 11
CON (n=24)	119 \pm 47	26 \pm 9

Ground reaction force (GRF), kinematic data, and tibial acceleration data were recorded and averaged from 5 running trials. Radiographs of the distal lower extremity were used to calculate the tibial area moment of inertia (Milgrom et al., 1989). Each subject underwent a structural evaluation by an experienced physical therapist.

Hypothesis 1.1: Runners who had sustained a previous TSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Subjects who had sustained a tibial stress fracture previously exhibited significantly greater instantaneous and average vertical loading rates (Figs. 1 and 2). No differences in impact peak, peak vertical and braking forces or leg stiffness were observed between the two groups (Table 2). This lack of difference in ground reaction force peaks between RTSF and CON groups has been reported previously (Crossley et al., 1999; Bennell et al., 2004). However, an increase in the average loading rate during braking was found in the RTSF group (Fig. 3). These existing studies did not consider loading rates in their comparisons; loading rates have consistently shown differences between RTSF and CON groups in our comparisons.

Average and instantaneous loading rates during braking have not been reported on in previous years. However, this secondary component of the ground reaction force peaks at approximately 50% of body weight and represents a substantial load to the lower extremity during the stance phase of running. It may be that differences here, multiplied over the 1000's of steps made by the distance runner, make a significant contribution to injury risk. As loading rates in the vertical direction have been increased in subjects with stress fractures, we decided to investigate loading rates during braking, in addition to peak braking force in the anteroposterior direction.

Additionally, individual joint stiffness, the change in joint angle over change in joint moment, was also investigated for the first time this year. Thus far, the global measure of leg stiffness during the first half of stance has not appeared to be related to the incidence of tibial stress fracture. Therefore, we chose to investigate the individual knee and ankle stiffness in the sagittal plane. We evaluated this stiffness over the period from foot strike to peak knee flexion, i.e. during loading of the lower extremity. Subjects with a history of tibial stress fracture had significantly higher knee joint stiffness than the control group (Fig. 4), but no difference was observed at the ankle. A stiffer knee may result in less shock attenuation by the lower extremity, thereby increasing the risk of stress related injuries.

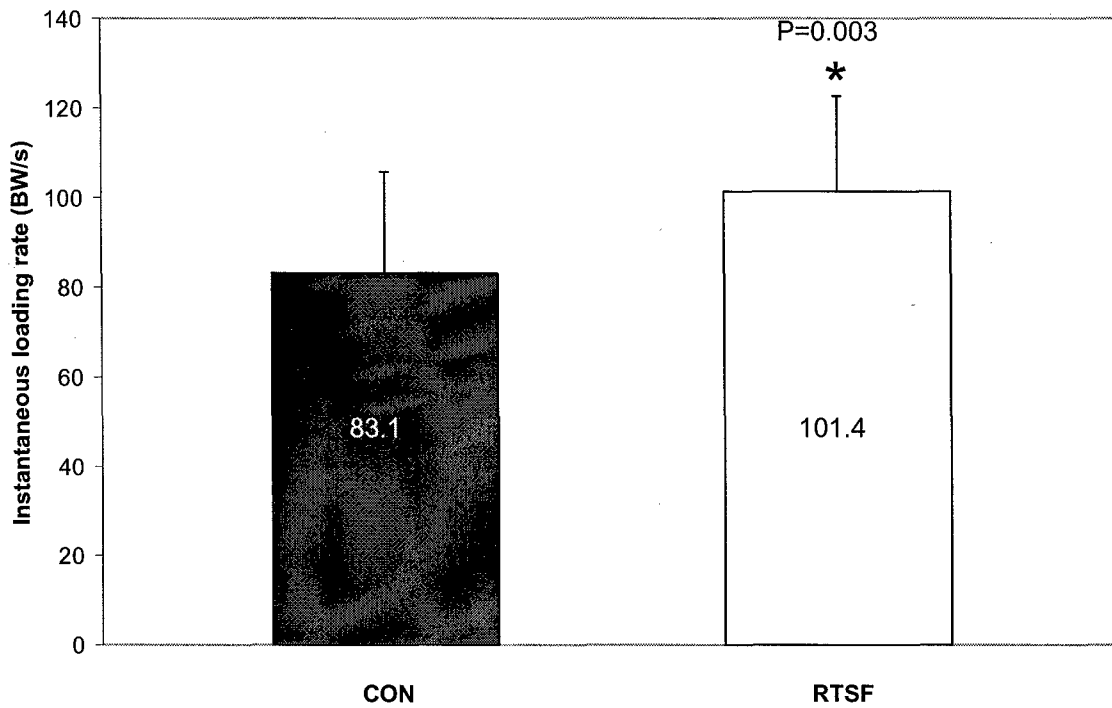


Figure 1: Instantaneous loading rate in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

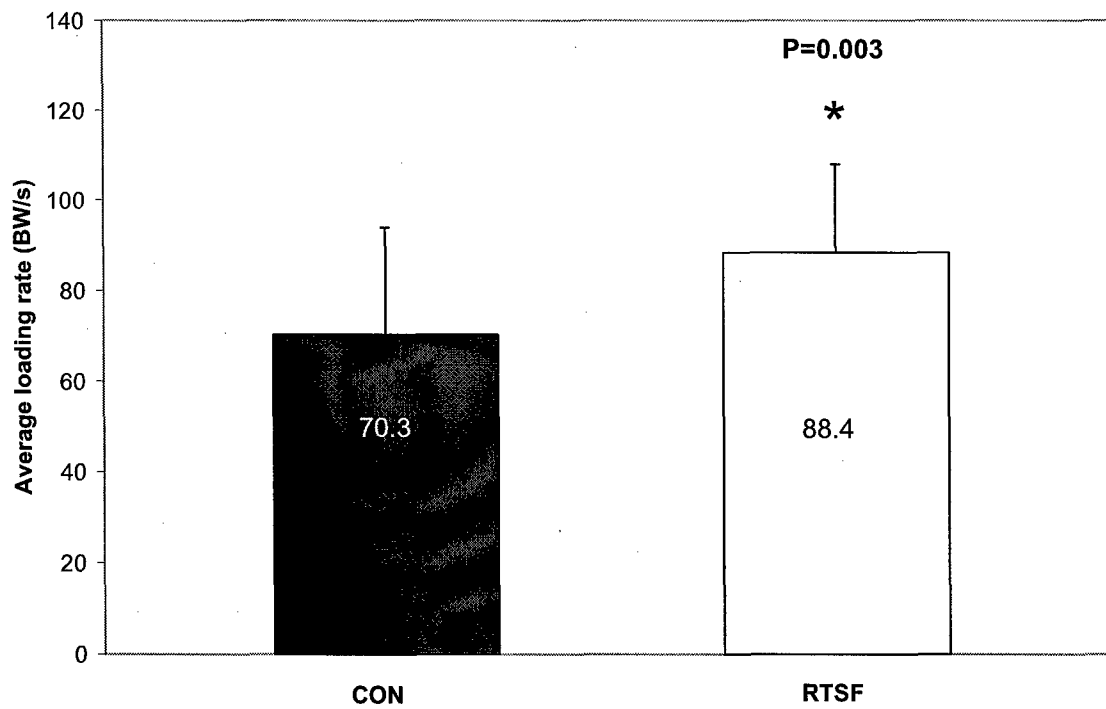


Figure 2: Average vertical loading rate in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

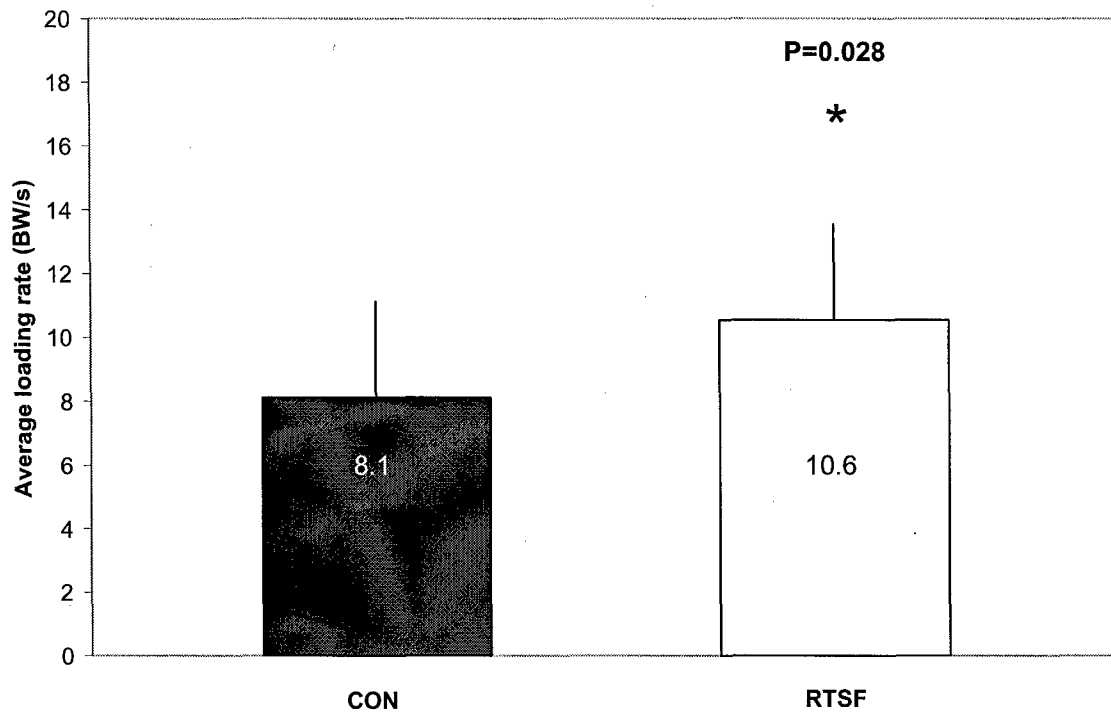


Figure 3: Average anteroposterior loading rate in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

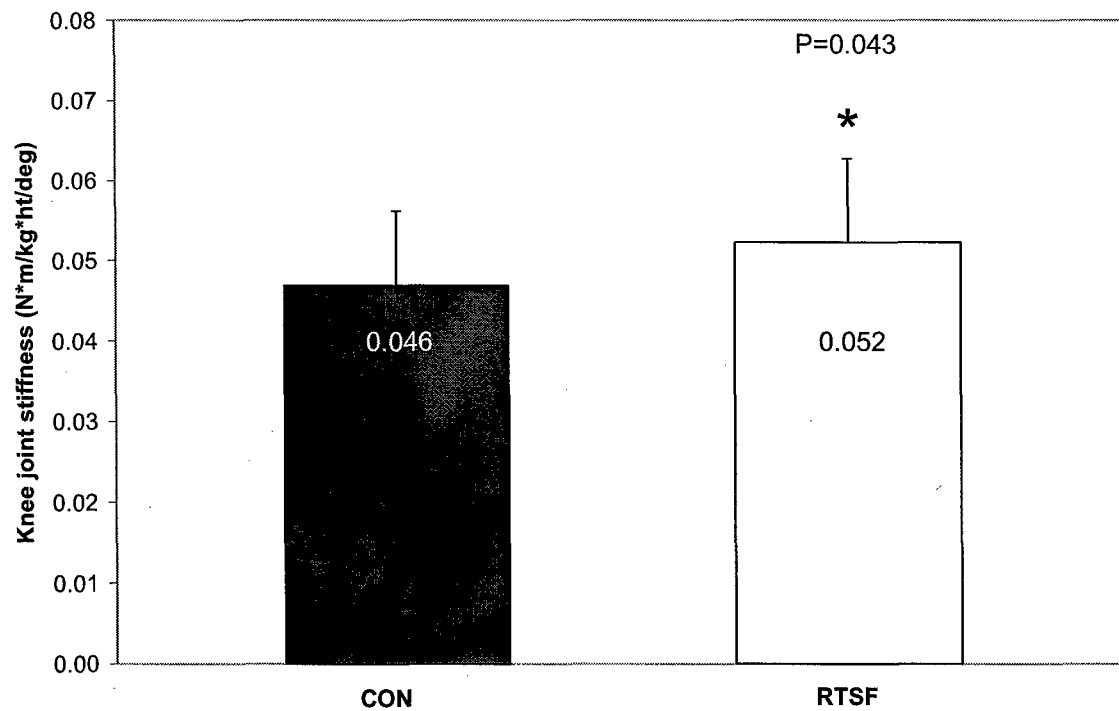


Figure 4: Average sagittal plane knee joint stiffness in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

Hypothesis 1.2: Runners who had sustained a previous TSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

Subjects who had sustained a previous tibial stress fracture exhibited significantly greater peak positive tibial acceleration than control subjects.. There was no difference in ankle dorsiflexion excursion between the two groups. Knee joint excursion was reduced in the TSF group, and this change was reflected in an increase in knee joint stiffness in these runners. A “stiff” runner will spend less time in contact with the ground (Farley and Gonzalez, 1996) and will attenuate less shock between the leg and the head (McMahon et al., 1987). This is in agreement with the findings of Farley and Gonzalez (1996) who suggested lower extremity stiffness and knee flexion excursion are highly correlated and may lead to stress fracture.

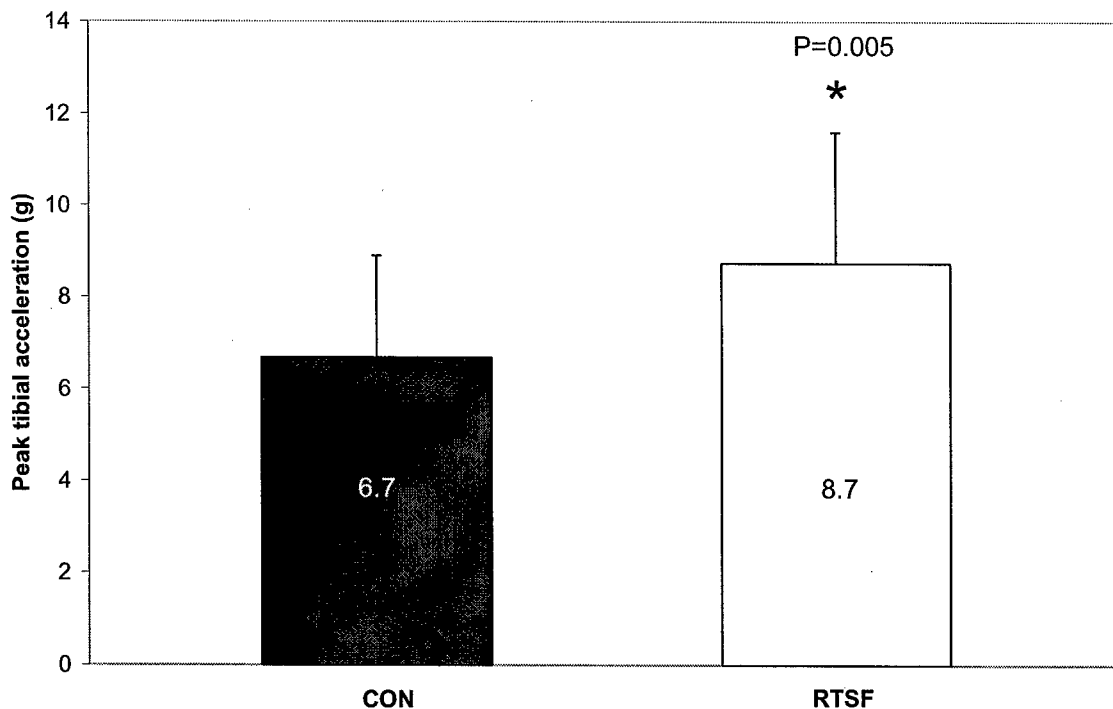


Figure 5: Peak positive tibial acceleration in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly greater than controls).

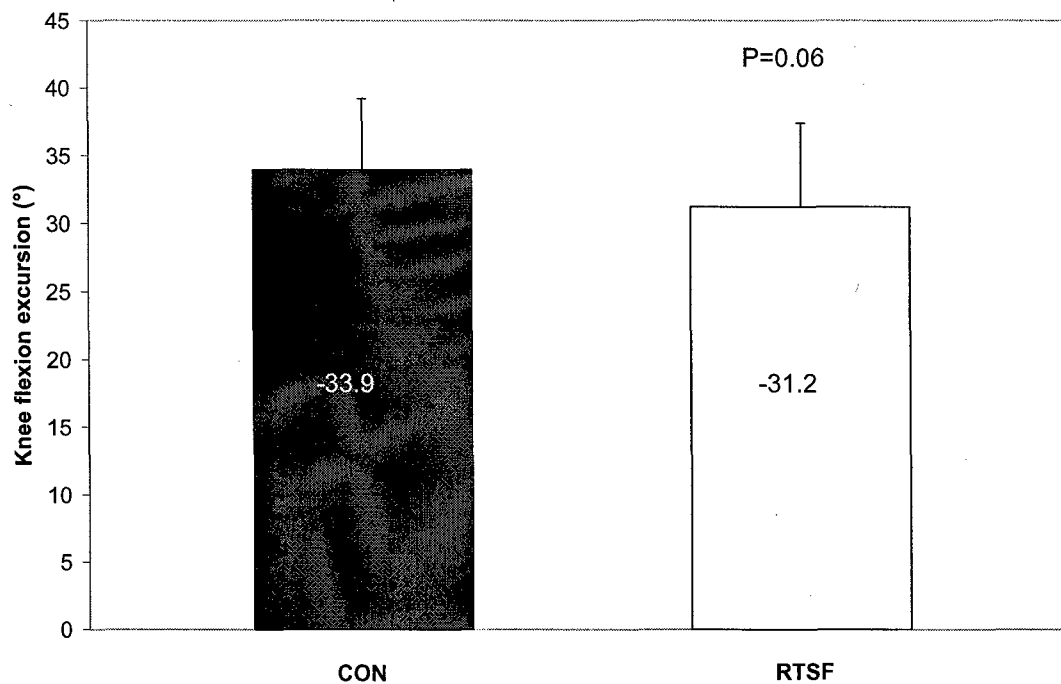


Figure 6: Knee flexion excursion in subjects who had a previous tibial stress fracture versus healthy controls (* = significantly less than controls).

Hypothesis 1.3: Runners who had sustained a previous TSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

Although specific structural characteristics have been associated with stress fracture injuries in male runners (Crossley et al., 1999; Milgrom et al., 1989), these groups of female distance runners did not demonstrate this relationship. No difference in tibial area moment of inertia or tibial varum was observed between the two groups (Table 2). These data are in agreement with recent work by Bennell et al. (2004), who found no difference in tibial bone geometry between female runners with and without a history of tibial stress fracture.

Table 2: Variables that showed no difference between subjects who had a previous tibial stress fracture and healthy controls.

	RTSF	CON	P value
Ankle dorsiflexion excursion	20.60 ± 5.48	22.09 ± 4.07	0.15
Peak vertical force (BW)	2.51 ± 0.19	2.53 ± 0.15	0.34
Impact peak (BW)	1.85 ± 0.19	1.77 ± 0.34	0.15
Peak braking force (BW)	-0.40 ± 0.07	-0.39 ± 0.05	0.34
Instantaneous braking load rate (BW/s)	21.93 ± 7.29	20.95 ± 5.36	0.30
Leg stiffness (kN/m)	8.78 ± 1.55	9.07 ± 1.49	0.28
Ankle jt stiffness (Nm/mass*ht/°)	0.33 ± 0.35	0.29 ± 0.38	0.36
Area moment of inertia (mm ⁴)	11403 ± 3224	12507 ± 3813	0.20
Tibial varum (°)	5.71 ± 2.31	6.43 ± 1.59	0.11

The observed decreases in knee joint excursion suggest that stiffness would be increased in the RTSF group. This was supported by the measure of knee joint stiffness that was included in this analysis, but not by the global measure of vertical leg stiffness. It appears that the stiffness of the individual joints, may be a more sensitive measure than the simple global measure employed initially. The observed increases in vertical loading rate and tibial acceleration support the notion that these impact-related kinetic variables may be related to the risk of tibial stress fracture. Additionally, the increase in average loading rate during braking suggests that this secondary plane may be of some importance in relation to tibial stress fracture.

There were no differences in tibial area moment of inertia between the RTSF and control groups. This is contrary to the study by Milgrom et al. (1989) who found a highly significant reduction in tibial area moment of inertia in the recruits who sustained a tibial stress fracture. However, they studied male military recruits compared to female runners examined in our study. The lack of a significant difference between the RTSF and control groups in this preliminary analysis suggests that other factors may be important in the etiology of tibial stress fractures in the female running population. Overall, area moment of inertia values in the RTSF group were 20% less than those reported by Milgrom et al. (1989). However, this is due to the smaller tibial width of females, which is correlated strongly with tibial area moment of inertia. Furthermore, the recent work by Bennell et al. (2004) suggests that these structural differences are not present in groups of female runners with and without a history of tibial stress fracture.

It should be noted that the kinetic differences between the RTSF and control groups are similar to those reported for the smaller group (n=20) of subjects that was considered last year. This year, our understanding of the differences between the groups has been enhanced by the inclusion of several extra stiffness and ground reaction force variables. These variables were included based on trends that we have observed in the data over the past year. We are continuing to refine our analysis by analyzing other variables during the first 50 ms of stance.

2) Summary of the prospective data obtained on female runners who sustained a tibial stress fracture during the study

Aim 2: Determine whether differences in structure and mechanics exist between subjects who sustain a tibial stress fracture (PTSF) to those who do not sustain a fracture.

Currently, only a relatively small number of participants have experienced tibial stress fractures (8 fractures in 6 subjects) during the follow-up period of the study. As advised by the reviewers of last year's report, we have analyzed PTSF data separately from tibial stress reactions. The PTSF group was compared to an age and mileage-matched control group (Table 3).

Table 3: Mean (\pm standard deviation) monthly running mileage and age of the PTSF and CON groups

	Mileage (miles/ month)	Age (years)
PTSF (n=6)	79 \pm 30	21 \pm 4
CON (n=6)	89 \pm 13	26 \pm 10

Hypothesis 2.1: Runners who sustained a TSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Due to the small number of subjects in each group, statistical analyses of these data were not conducted. Instead, we have operationally defined a difference of 15% between the groups as indicating a clinically significant difference. In this group of PTSF subjects, we found several differences in comparison to the matched control group. As expected, impact peak (Fig. 7) and instantaneous loading rate (Fig. 8) were higher in the PTSF group. However, loading rates during braking (Figs. 9 and 10) were lower in the PTSF group compared to controls. These lower values in the PTSF group were contrary to our hypotheses and to our retrospective data. However, these preliminary results from the TSFs sustained during the study should be interpreted cautiously, since the number of subjects involved is small.

Due to the small number of subjects involved, these data are sensitive to the specific subjects sampled and can change noticeably with the addition or exclusion of even one individual's data. As the number of subjects with prospective TSF increases, this problem should diminish.

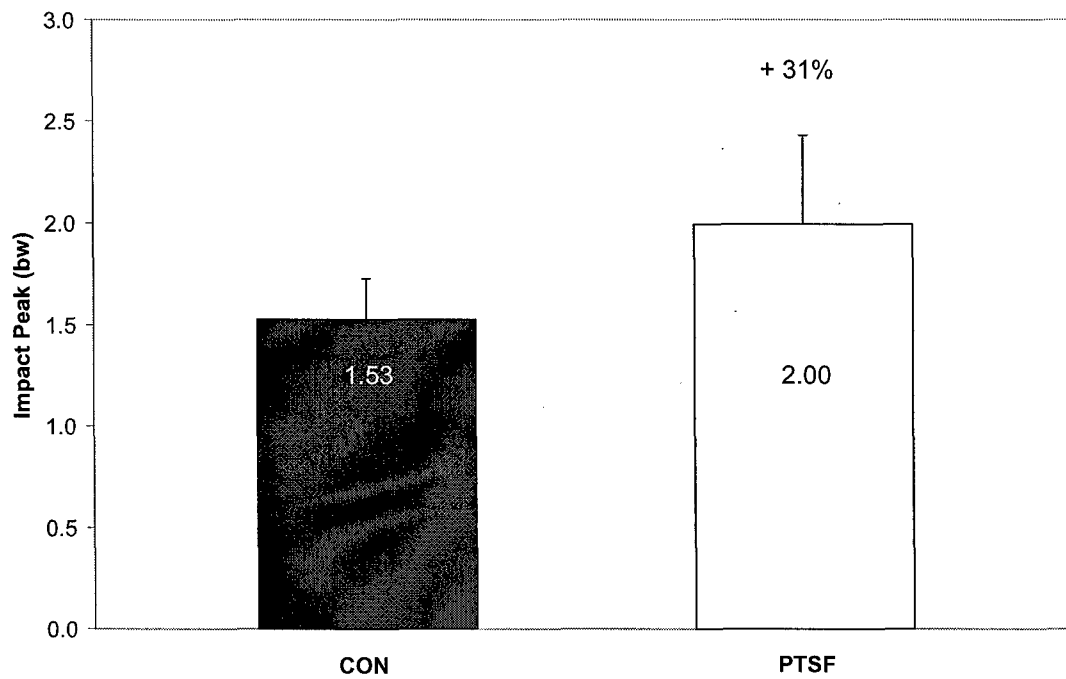


Figure 7: Impact peak during braking in subjects who developed a tibial stress fracture versus healthy controls.

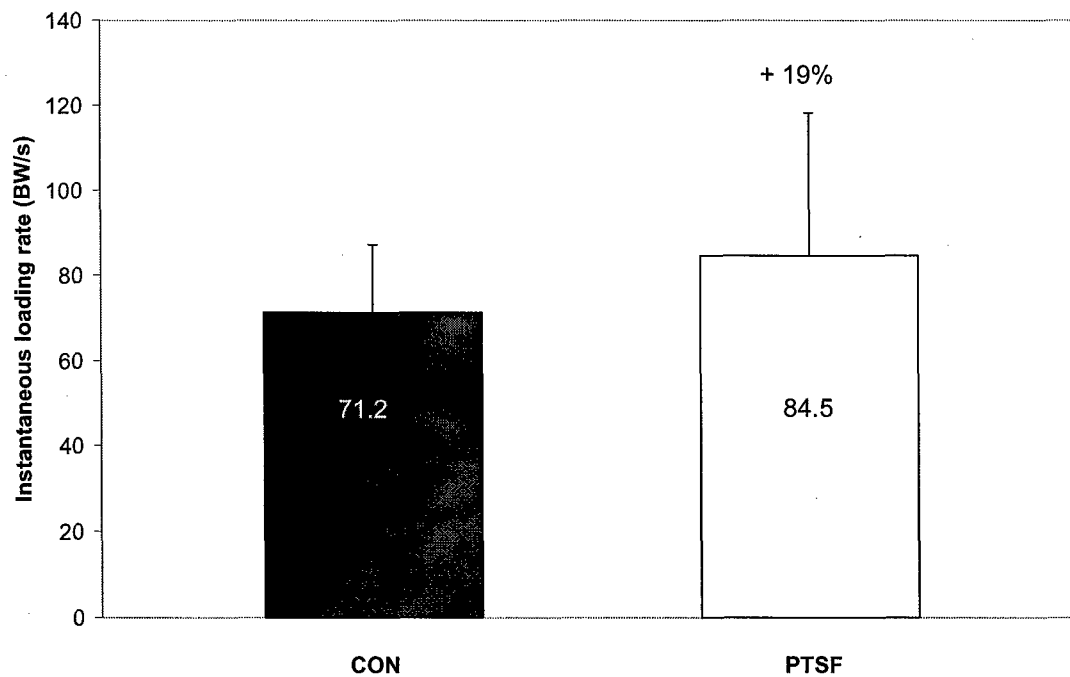


Figure 8: Instantaneous loading rate during braking in subjects who developed a tibial stress fracture versus healthy controls.

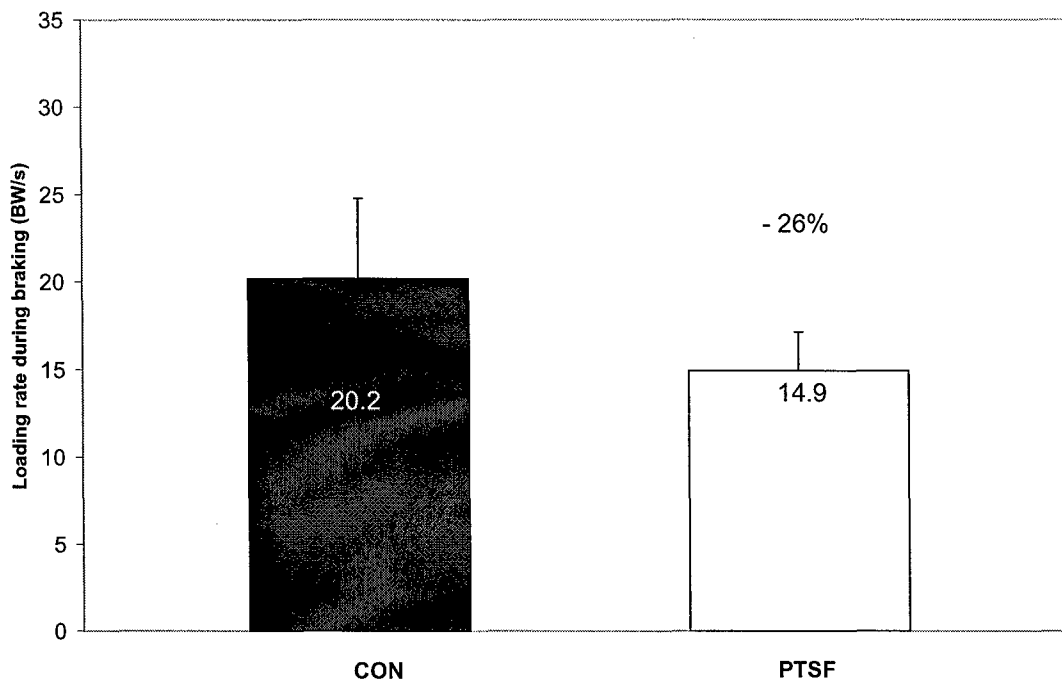


Figure 9: Instantaneous loading rate during braking in subjects who developed a tibial stress fracture versus healthy controls.

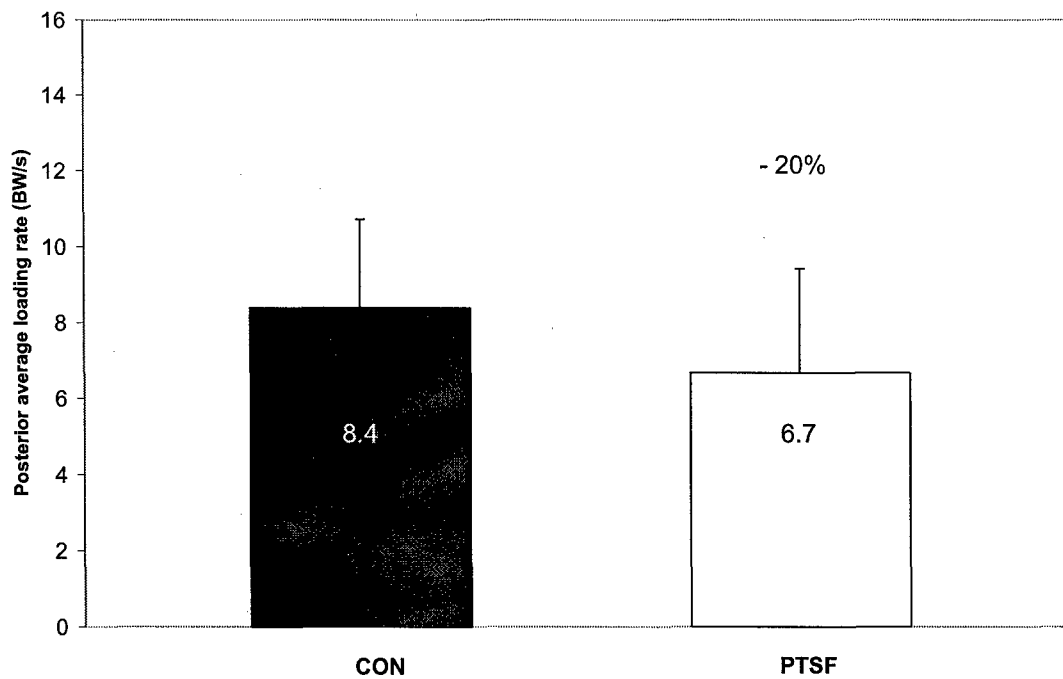


Figure 10: Average loading rate during braking in subjects who developed a tibial stress fracture versus healthy controls.

Hypothesis 2.2: Runners who sustained a PTSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

The prospective TSF group exhibited no difference in these variables compared to the healthy controls (Table 4). This differs from the retrospective TSF group, which had reduced knee flexion excursion and tibial acceleration compared to the control group. In addition, there were some individuals within the PTSF group who had excessively high values. For example, two PTSF subjects had tibial shock value over 9g, higher than the mean value for the RTSF group. These same two subjects also had instantaneous vertical loading rates over 100 BW/s, also higher than the average of the RTSF group. Although they did not meet the criteria of 15% difference, it should be noted that PPA (shock) was 8% higher, average vertical loading rates were 13% higher and knee stiffness was 12% higher in the PTSF group as expected.

Hypothesis 2.3: Runners who sustained a PTSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

Tibial varum was 20% lower in the prospective TSF group compared to the healthy controls (Fig. 11).

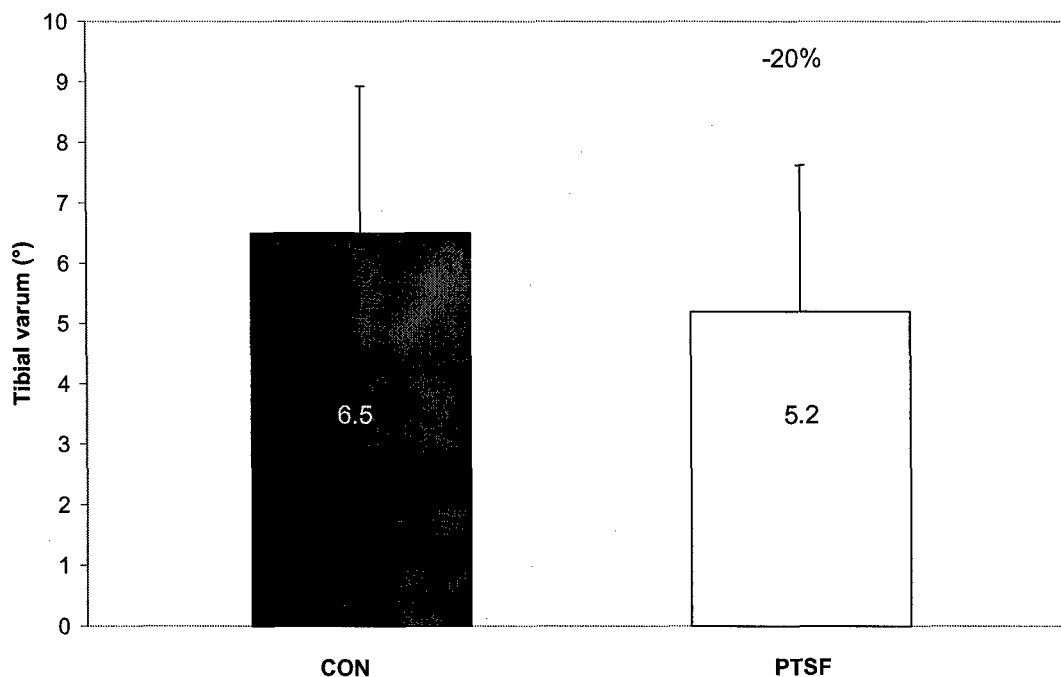


Figure 11: Tibial varum in subjects who developed a tibial stress fracture versus healthy controls.

Table 4: Variables that showed no difference between subjects who had a prospective tibial stress fracture and healthy controls.

	PTSF	CON	% diff.
Peak vertical force (BW)	2.54 ± 0.11	2.60 ± 0.11	-2.4
Average vertical load rate (BW/s)	70.66 ± 33.95	62.21 ± 12.60	13.6
Peak positive tibial acceleration (g)	6.42 ± 3.30	5.94 ± 0.92	8.1
Peak braking force (BW)	-0.35 ± 0.05	-0.38 ± 0.06	-8.2
Leg stiffness	7.99 ± 0.86	9.26 ± 1.66	-13.7
Ankle joint stiffness (Nm/mass*ht/°)	0.045 ± 0.012	0.045 ± 0.005	-1.3
Knee joint stiffness (Nm/mass*ht/°)	0.045 ± 0.015	0.041 ± 0.005	11.8
Ankle dorsiflexion excursion (°)	20.7 ± 3.0	22.0 ± 2.1	-5.7
Knee flexion excursion (°)	35.3 ± 4.2	36.6 ± 3.9	-3.5
Area moment of inertia (mm ⁴)	10,963 ± 942	11,788 ± 2,316	-7.0

In conclusion, the limited amount of data so far available for prospective tibial stress fractures partially reflects differences observed in the retrospective tibial stress fracture group. However, results suggest that differences, though not yet significant, are in the expected direction. As statistical power increases with additional prospective fractures, it is hoped that these differences will become more clear.

3) Summary of the prospective data obtained on ALL of the lower extremity stress fractures: comparison to uninjured female runners

Aim 3: Determine whether differences in structure and mechanics exist between subjects who sustain a lower extremity fracture (PSF) to those who do not sustain a fracture.

Due to the small number of participants who have experienced a TSF, we also analyzed all prospective stress fracture injuries combined (6 TSF, 6 femoral, 1 pelvic, 2 fibular, 5 metatarsal).

Table 5: Mean (± standard deviation) monthly running mileage and age of the PSF and CON groups

	Mileage (miles/ month)	Age (years)
PSF (n=20)	99 ± 36	26 ± 9
CON (n=20)	107 ± 27	28 ± 10

Hypothesis 3.1: Runners who sustained a PSF would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Similar differences between the PSF and control group were found as were observed in the PTSF group alone. A trend toward a higher vertical impact peak and instantaneous loading rate in the PSF group reflected that found in the PTSF group (Figs. 12 and 13).

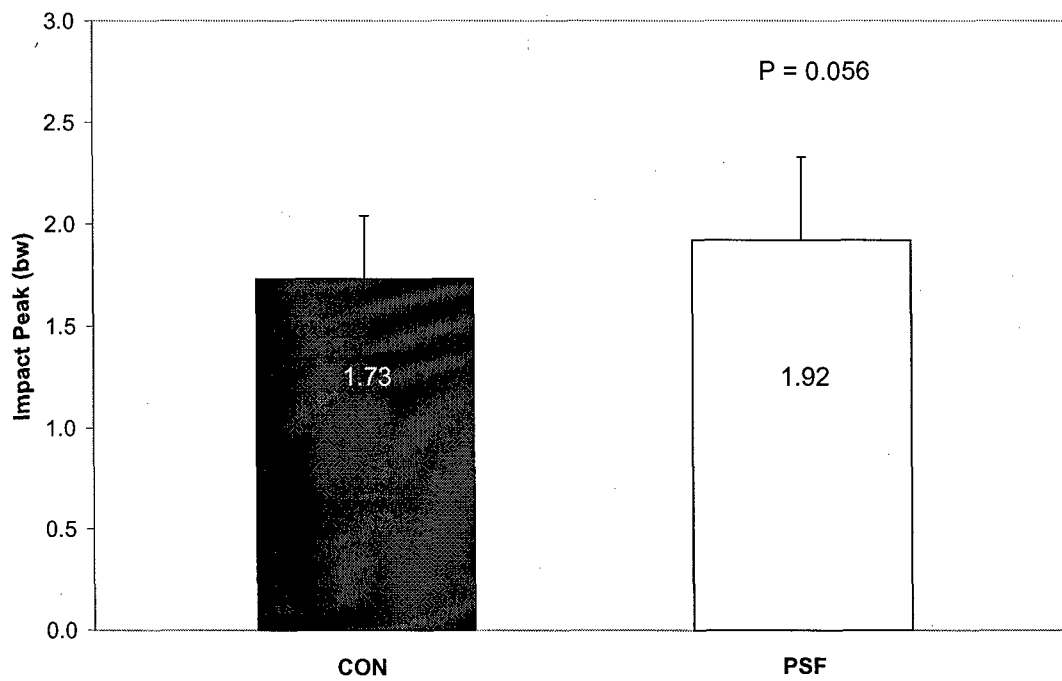


Figure 12: Impact peak in subjects who developed a stress fracture versus healthy controls.

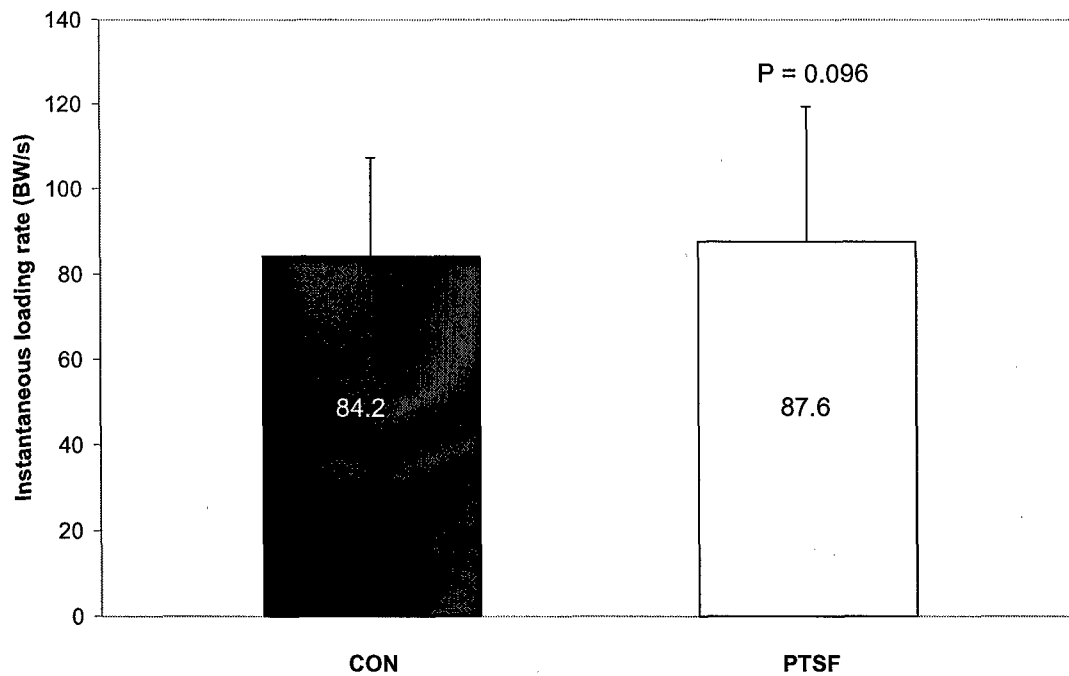


Figure 13: Instantaneous vertical loading rate in subjects who developed a stress fracture versus healthy controls.

Hypothesis 3.2: Runners who sustained a PSF would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

Ankle dorsiflexion and knee flexion excursion showed a trend towards being lower in the PSF group compared to controls, as expected (Figs. 14 and 15). This suggests that stiffness might be higher in these joints, however that is not the case as of yet. While not statistically significant, PPA was 10% higher in the runners who developed a Lower extremity stress fracture (Table 6).

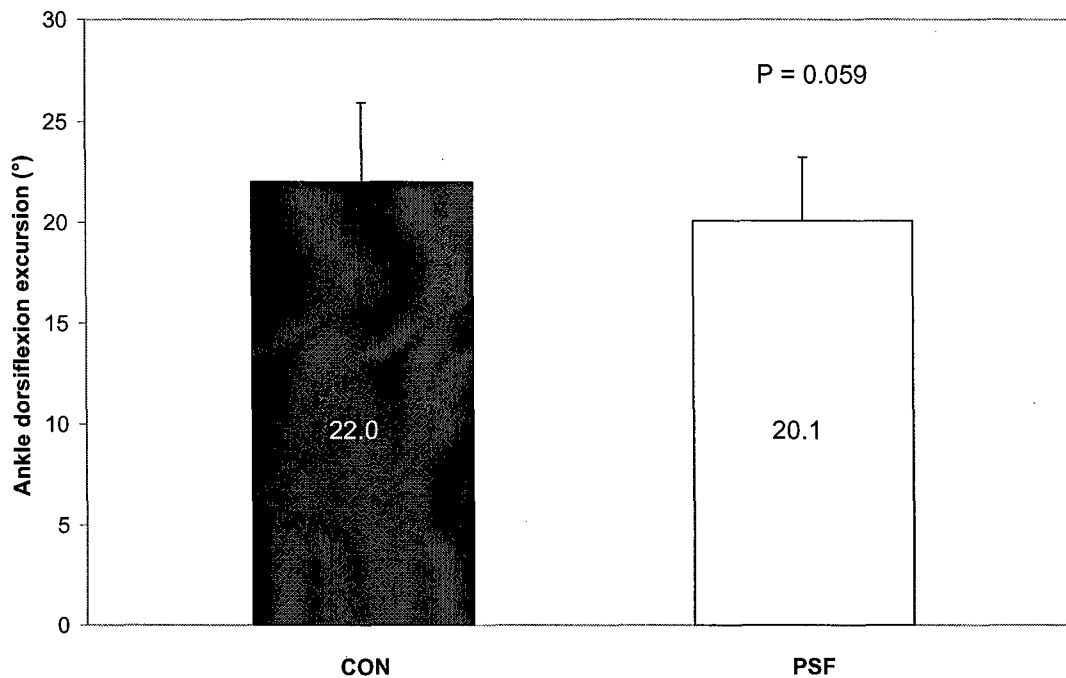


Figure 14: Ankle dorsiflexion excursion in subjects who developed a stress fracture versus healthy controls.

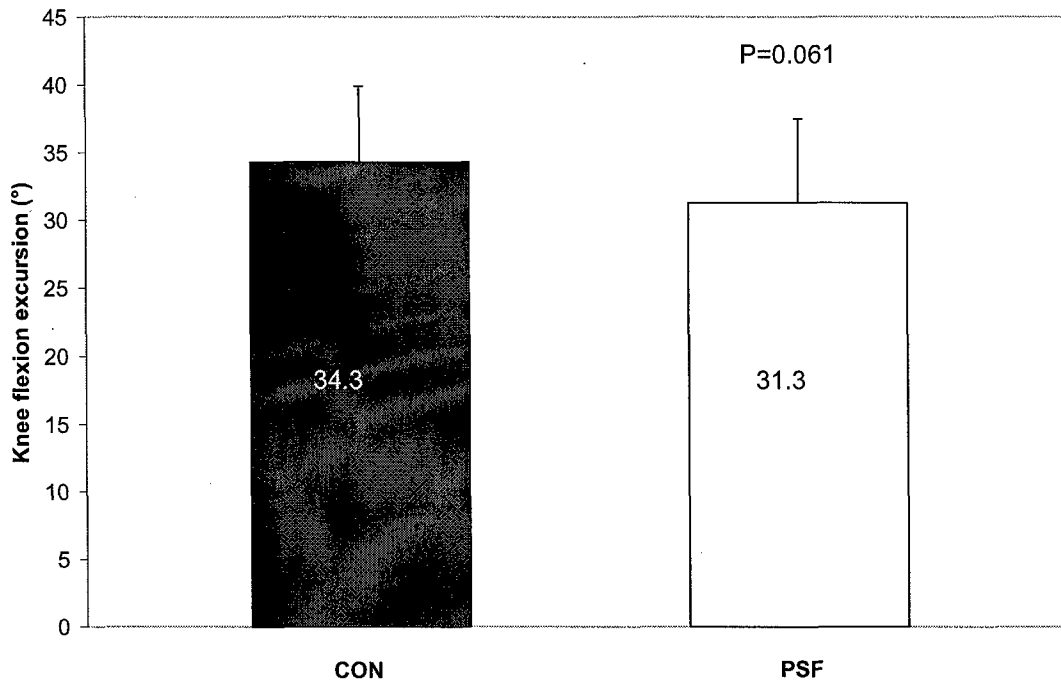


Figure 15: Knee flexion excursion in subjects who developed a stress fracture versus healthy controls.

Hypothesis 3.3: Runners who sustained a PSF would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

This group of PSF subjects demonstrated a 35% decrease in tibial varum, which is opposite to what we expected, but also found in the PTSF group (Fig. 16). We expected that greater tibial varum would be associated with stress fractures (especially tibial) secondary to the increased bending moment on the leg.

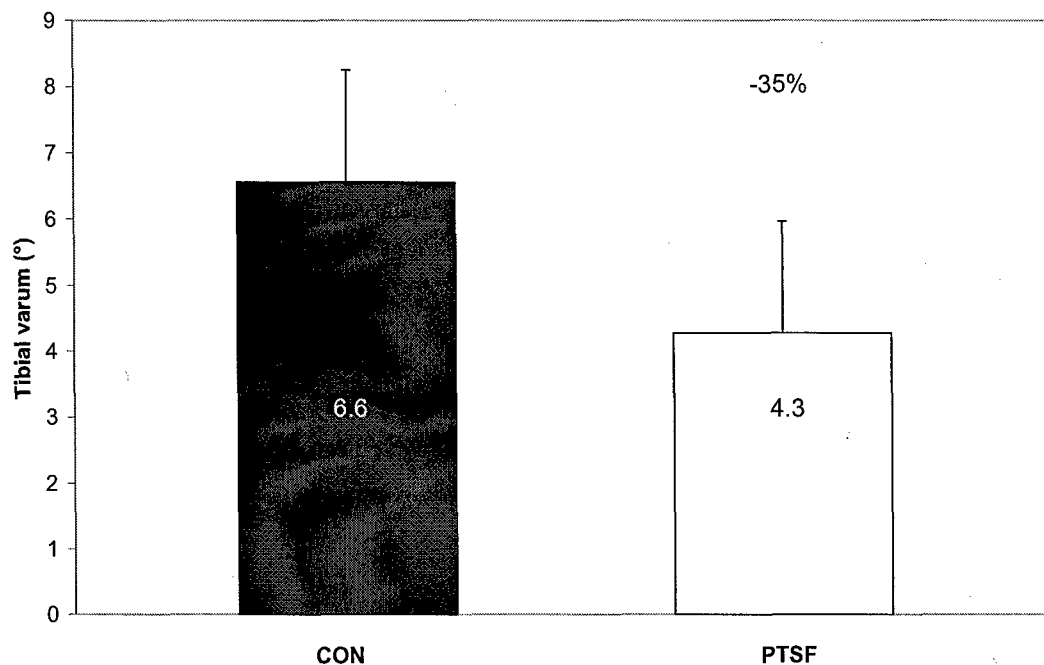


Figure 16: Tibial varum in subjects who developed a lower extremity stress fracture versus healthy controls.

Table 6: Variables that showed no difference between subjects who had a prospective stress fracture and healthy controls.

	PSF	CON	P value
Peak vertical force (BW)	2.46 ± 0.20	2.55 ± 0.14	#
Average vertical loading rate (BW/s)	73.47 ± 31.66	70.53 ± 29.44	0.339
Peak braking force (BW)	-0.37 ± 0.07	-0.36 ± 0.18	0.385
Braking instantaneous load rate (BW/s)	18.66 ± 6.75	21.56 ± 5.43	#
Braking average load rate (BW/s)	7.34 ± 2.25	7.96 ± 3.66	#
Peak tibial acceleration	7.79 ± 5.37	7.06 ± 2.57	0.296
Vertical leg stiffness (kN/m)	8.71 ± 2.80	8.54 ± 1.67	0.400
Ankle joint stiffness (Nm/mass*ht ^o)	0.042 ± 0.012	0.047 ± 0.005	#
Knee joint stiffness (Nm/mass*ht ^o)	0.043 ± 0.013	0.045 ± 0.009	#
Tibial area moment of inertia	12,222 ± 1,919	11,747 ± 2734	#

indicates that the difference between groups was in the opposite direction to the hypothesis. Use of the one-tailed t-test precludes interpretation of these data.

4) Summary of pre and post injury data from six individuals with prospective tibial stress fractures

Aim 4: Compare mechanics of individuals with healed tibial stress fractures to their mechanics prior to the fracture to determine whether compensation for injury occurs. As advised by the reviewers of last year's report, we have not included tibial stress reactions in this comparison (last year we reported on 4 TSFs and 4 TSRs). We consider group differences of 15% or more to be clinically significant. With the addition of more subjects in the future, statistical analysis will be performed.

Hypothesis 4.1: Runners with healed TSFs would not exhibit changes in kinetic variables including instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to their pre-injury status.

Table 7: Mean kinetic variables for six prospective tibial stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Impact peak (BW)	2.00 \pm -0.44	2.01 \pm 0.39	0.8
Peak vertical force (BW)	2.54 \pm 0.11	2.48 \pm 0.19	-2.4
Vertical instantaneous load rate (BW/s)	84.54 \pm 33.71	79.05 \pm 36.29	-6.5
Vertical average load rate (BW/s)	70.66 \pm 33.95	63.58 \pm 38.71	-10.0
Peak braking force (BW)	-0.35 \pm 0.05	-0.36 \pm 0.05	4.9
Vertical leg stiffness (kN/m)	7.99 \pm 0.86	7.94 \pm 0.80	-0.6
Ankle joint stiffness (Nm/mass*ht/°)	0.042 \pm 0.005	0.045 \pm 0.006	8.7

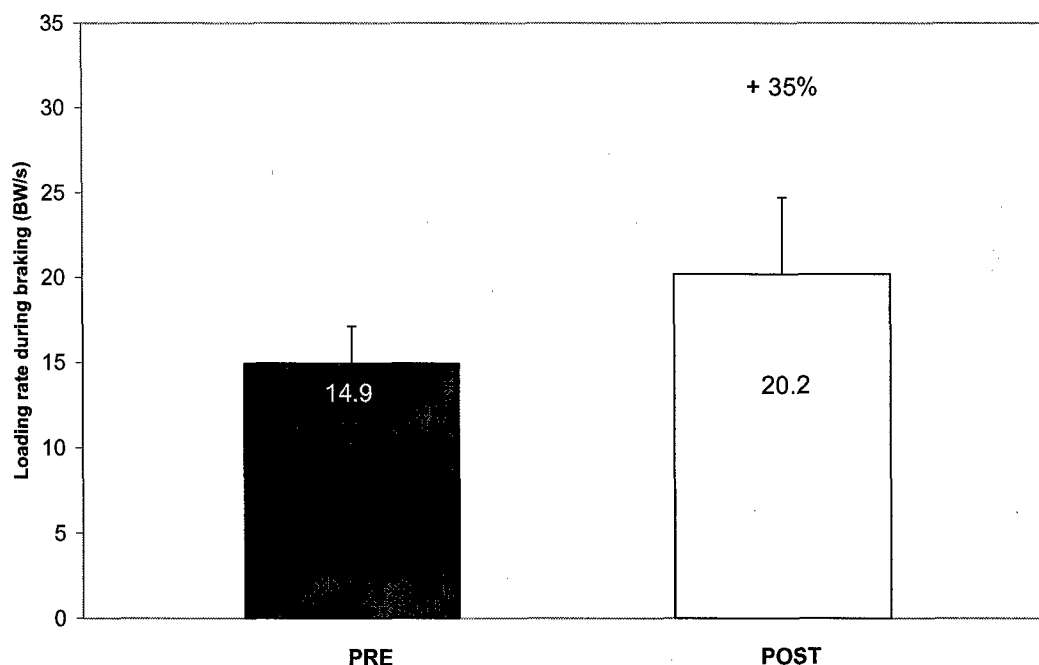


Figure 17: Instantaneous loading rate during braking pre and post tibial stress fracture.

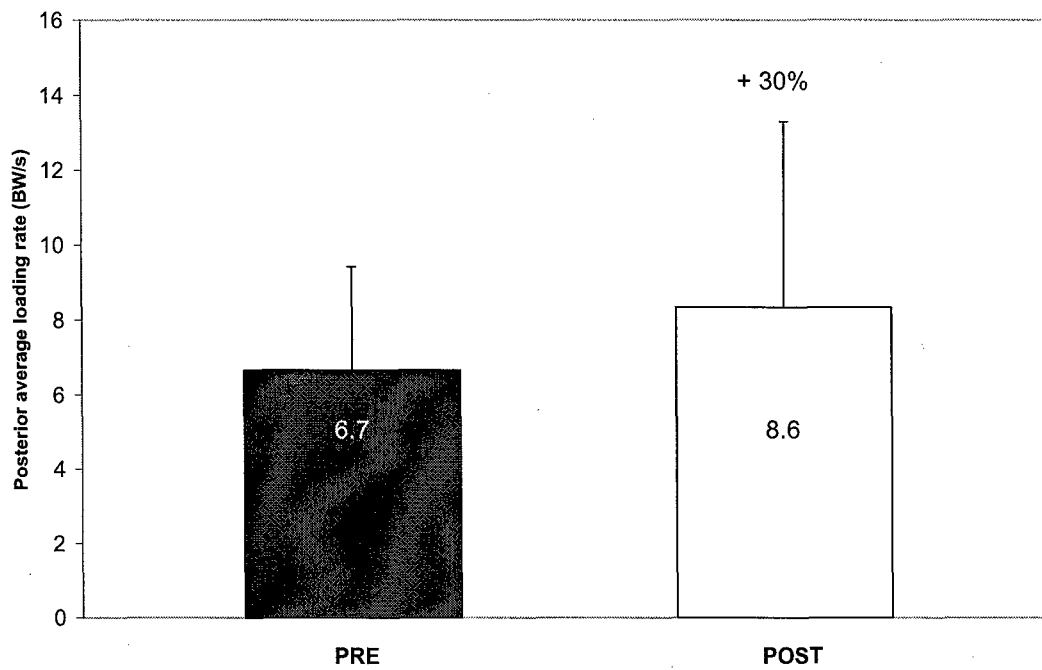


Figure 18: Average loading rate during braking pre and post tibial stress fracture.

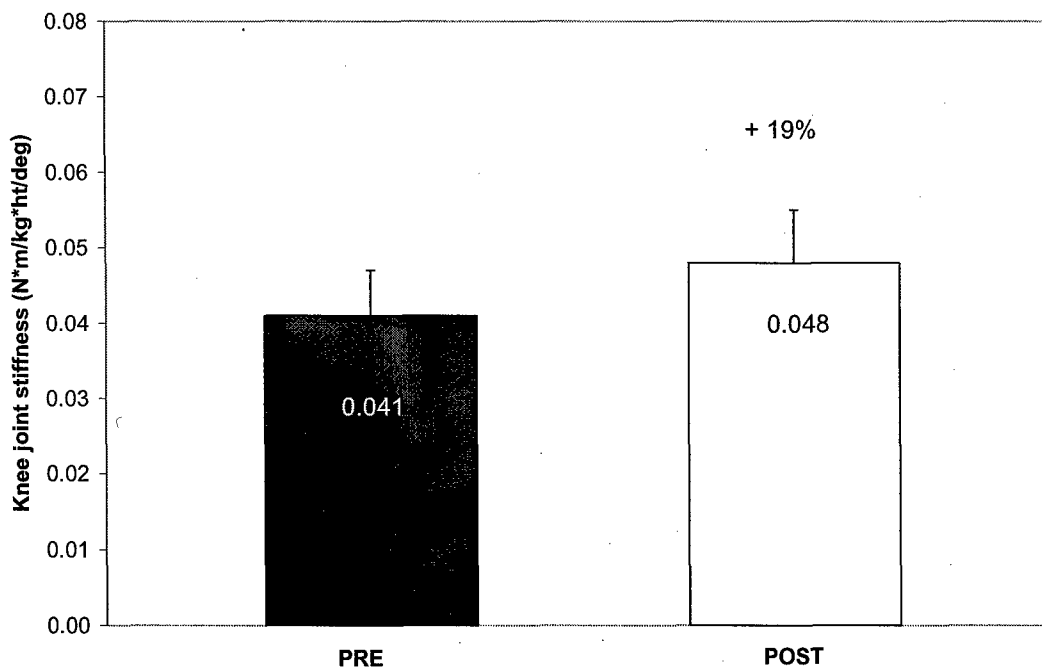


Figure 19: Knee joint stiffness pre and post tibial stress fracture.

At this stage, there are only minimal differences between pre and post injury kinetic variables for runners who sustained a TSF during the study, with the exception of loading rates during braking. Both instantaneous and average loading rates during braking were increased at the post- injury visit. These shear loading rates indicate the magnitude of bending loads that the lower extremity is subject to, in addition to the compressive loading that occurs during initial weight acceptance in stance. It has been shown that anterior-posterior bending strength is related to the risk of tibial stress fracture (Milgrom et al., 1989). Therefore, the magnitude of anterior-posterior loading rates may be directly related to stress fracture. The secondary planes of ground reaction force are often overlooked in gait analyses, but these substantial changes indicate that they are worthy of further investigation in relation to stress fracture injuries in runners. An increase in knee joint stiffness is also apparent, which may contribute to an increased injury risk.

Hypothesis 4.2: Runners with healed TSFs would not exhibit changes in kinematic variables including peak tibial acceleration, ankle dorsiflexion excursion and knee flexion excursion compared to their pre-injury status.

Table 8: Mean kinematic variables for six prospective tibial stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Peak tibial acceleration (g)	6.48 \pm 3.23	7.04 \pm 3.07	8.6
Ankle dorsiflexion excursion (°)	20.7 \pm 3.0	20.4 \pm 1.5	-1.4
Knee flexion excursion (°)	35.3 \pm 4.2	33.9 \pm 2.8	-4.0

Furthermore, a small increase in tibial shock occurred following recovery from injury. Since stress fractures are essentially fatigue fractures of the bone, their occurrence relates to the load per cycle and the number of cycles. Increasing either of these factors increases the risk of exceeding the fatigue limit of the tissue. Both loading rates during braking and tibial shock indicate the magnitude of compression loading per cycle, therefore higher values indicate increased risk.

These data suggest that there may be some changes in the gait of runners who sustain a stress fracture following recovery from the fracture. There are increases in several loading related variables, which may help to explain the 36% incidence of reinjury following a lower extremity stress fracture in runners.

Due to the low numbers, these data provide only a suggestion of the changes that may occur following recovery from such an injury. As more tibial stress fractures occur in the study population, statistical analysis of the changes will be carried out to determine whether there is a change between pre and post tibial stress fracture mechanics. If mechanics associated with stress fractures either remain the same or increase once the stress fracture is healed, there is a need to address these abnormal mechanics. We have begun to develop a gait retraining program aimed at reducing loads associated with runners at risk.

If these findings are seen consistently as additional subjects are added, there may be a need to retrain the gait patterns of runners who sustain tibial stress fractures, to reduce the risk of recurring fractures. In addition, if differences between pre and post injury mechanics persist, this provides further support of the need for prospective studies.

5) Summary of pre and post injury data from all prospective lower extremity stress fractures

Aim 5: Compare mechanics of individuals with healed lower extremity stress fractures to their mechanics prior to the fracture to determine whether compensation for injury occurs. This group comprises 1 pelvic, 3 femoral, 6 tibial and 2 metatarsal stress fractures.

With the relatively small number of participants who have experienced tibial stress fractures prospectively and returned for a reassessment, we have extended this comparison to include all lower extremity stress fractures. Again, we consider group changes of 15% or more to be clinically significant. With the addition of more subjects in the future, statistical analysis will be performed.

Hypothesis 4.1: Runners with healed SFs would not exhibit changes in kinetic variables including instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to their pre-injury status.

Table 9: Mean kinetic variables for 12 prospective lower extremity stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Impact peak (BW)	1.92 ± 0.37	2.00 ± 0.40	4.4
Peak vertical force (BW)	2.41 ± 0.23	2.44 ± 0.25	1.3
Vertical instantaneous load rate (BW/s)	87.31 ± 29.84	86.39 ± 38.55	-1.0
Vertical average load rate (BW/s)	73.57 ± 29.49	71.74 ± 37.97	-2.5
Peak braking force (BW)	-0.35 ± 0.08	-0.38 ± 0.09	6.9
Braking average load rate (BW/s)	7.36 ± 2.57	8.17 ± 3.90	11.0
Vertical leg stiffness (kN/m)	8.70 ± 3.09	7.71 ± 0.85	-11.4
Ankle joint stiffness (Nm/mass*ht ⁰)	0.040 ± 0.013	0.046 ± 0.005	13.9

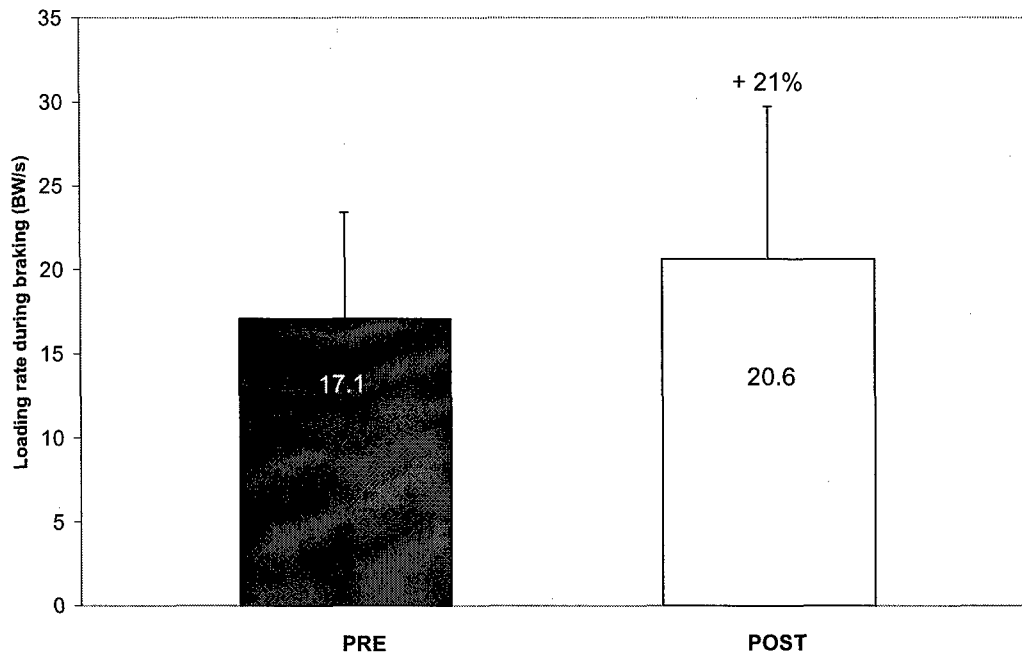


Figure 20: Instantaneous loading rate during braking pre and post lower extremity stress fracture.

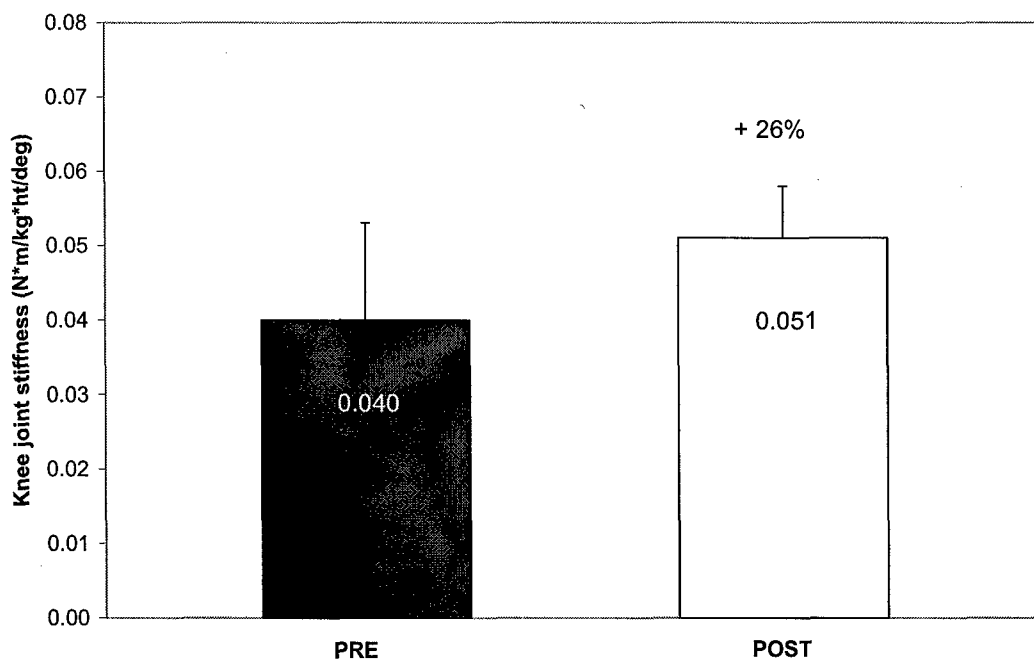


Figure 21: Knee joint stiffness pre and post lower extremity stress fracture.

Similar to the PTSF data, responses are variable. However, there was a general trend of increased anteroposterior loading rates during braking in this group, but not vertical

loading characteristics. Increases in ankle and knee joint stiffness are also apparent post stress fracture, again reflecting changes observed in the PTSF group.

Hypothesis 4.2: Runners with healed SFs would not exhibit changes in kinematic variables including peak tibial acceleration, ankle dorsiflexion excursion and knee flexion excursion compared to their pre-injury status.

Table 10: Mean kinematic variables for 12 prospective lower extremity stress fracture subjects pre and post injury.

	PRE	POST	% Difference
Peak tibial acceleration (g)	7.67 ± 4.21	7.90 ± 3.53	2.9
Ankle dorsiflexion excursion (°)	20.9 ± 2.8	20.8 ± 1.8	0.0
Knee flexion excursion (°)	32.0 ± 6.5	31.8 ± 4.7	-0.5

No changes were noted in these variables.

6) Summary of the prospective data obtained on female runners who sustained a tibial stress reaction during the study

Determine whether differences in structure and mechanics exist between subjects who sustain a tibial stress reaction (PTSR) to those who do not sustain a fracture.

Tibial stress reactions have been operationally defined as bony pain specifically along the distribution of the tibia that is worsened with impact loading and relieved with rest. There is indication in the literature (Fredericson et al., 1995) that these stress reactions are the early stage of a stress fracture. As advised by the reviewers of last year's report, we have not pooled the PTSF data with data from tibial stress reactions, however we feel that this group represents a precursor to tibial stress fracture and, therefore have included it here. The PTSR group (12 TSR in 7 individuals) was compared to the control group used in comparison to PTSF.

Runners who sustained a PTSR would exhibit differences in kinetic variables including increased instantaneous and average vertical loading rates, peak vertical and braking forces and stiffness compared to controls.

Due to the small number of subjects in each group (n=7), statistical analyses of these data were not conducted. Instead, we have operationally defined a difference of 15% between the groups as indicating a clinically significant difference. In this group of PTSR subjects, we found several differences in comparison to the matched control group. As expected, impact peak and instantaneous loading rate were higher in the PTSR group (Table 11). However, instantaneous loading rate during braking was lower in the PTSR group compared to controls. This lower value in the PTSR group was contrary to our hypothesis. These preliminary results from the TSRs sustained during the study should be interpreted cautiously, since the number of subjects involved is small.

Due to the small number of subjects involved, these data are sensitive to the specific subjects sampled and can change noticeably with the addition or exclusion of even one individual's data.

Runners who sustained a PTSR would exhibit differences in kinematic variables including increased peak positive tibial acceleration, decreased ankle dorsiflexion excursion and decreased knee flexion excursion compared to controls.

The prospective TSR group exhibited increased tibial acceleration compared to the healthy controls. This is in partial agreement with the retrospective TSF group, which had reduced knee flexion excursion and tibial acceleration compared to the control group.

Runners who sustained a PTSR would exhibit differences in structural variables including increased tibial varum and decreased tibial area moment of inertia compared to healthy controls.

Tibial varum was unexpectedly lower (by 34%) in the prospective TSR group compared to the healthy controls.

Table 11: Variables that showed no difference between subjects who had a prospective tibial stress reaction and healthy controls.

	PTSF	CON	% diff.
Impact peak (BW)	1.80 ± 0.40	1.53 ± 0.20	19.0
Peak vertical force (BW)	2.40 ± 0.20	2.60 ± 0.11	-6.3
Average vertical load rate (BW/s)	70.73 ± 29.34	62.21 ± 12.6	13.7
Instantaneous vertical load rate (BW/s)	82.43 ± 27.55	71.22 ± 16.03	15.7
Peak positive tibial acceleration (g)	7.47 ± 4.26	5.93 ± 0.92	25.9
Peak braking force (BW)	-0.33 ± 0.14	-0.38 ± 0.06	-13.1
Average braking load rate (BW/s)	9.58 ± 3.56	8.39 ± 2.33	14.3
Instantaneous braking load rate (BW/s)	15.74 ± 6.05	20.19 ± 4.59	-22.0
Leg stiffness	7.87 ± 1.26	9.26 ± 1.66	-15.1
Ankle dorsiflexion excursion (°)	20.0 ± 3.5	22.0 ± 2.1	-8.7
Knee flexion excursion (°)	34.5 ± 3.4	36.6 ± 3.9	-5.7
Tibial varum (°)	4.3 ± 1.7	6.5 ± 2.4	-34.1
Area moment of inertia (mm ⁴)	12424 ± 2188	11788 ± 2316	5.4

In conclusion, the limited amount of data so far available for prospective tibial stress reactions only partially reflects differences observed in the retrospective tibial stress fracture group. Differences were found in ground reaction force variables, in both the same and opposite direction as found in the retrospective groups. This may partly be a consequence of the small subject group. By concentrating our final recruitment on high risk groups, we hope to have more occurrences of prospective tibial stress fracture in the next 12 month period. This will enable us to compare a larger group to uninjured controls, to try and elucidate pre-existing differences between runners who sustain a tibial stress fracture and those who do not.

7) List of Publications

Since the last report, three manuscripts have been submitted to peer-reviewed journals. One is in review with *Medicine and Science in Sports and Exercise*, the second is in review with *Journal of Biomechanics* and the third is in review with *American Journal of Sports Medicine*. These articles are included in Appendix A and the references are as follows:

Milner C E, Davis I S and Hamill J (2005) Free moment as a predictor of tibial stress fracture in distance runners. Submitted to *Journal of Biomechanics*, May 2005.

Milner C E, Ferber R, Pollard C D, Hamill J and Davis I S (2005) Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. Submitted to *Medicine and Science in Sports and Exercise*, February 2005.

Ferber R, Davis I S, Milner C E, Hamill J and Pollard C D (2005) Retrospective Biomechanical Investigation of Iliotibial Band Syndrome in Competitive Female Runners. Submitted to *American Journal of Sports Medicine*.

Additionally, six additional abstracts have been submitted and accepted for presentation since the last report. Three abstracts were presented at the American College of Sports Medicine National Meeting in Nashville, Tennessee in June 2005 and three will be presented at the International Society of Biomechanics and American Society of Biomechanics Combined Meeting in Cleveland, Ohio in August 2005. These abstracts are included in Appendix B and the references are provided below.

Hamill J, Haddad J M, Milner C E and Davis I S (2005) Intralimb coordination in female runners with tibial stress fractures. *Proceedings of the International Society of Biomechanics XXth Congress, XX*.

Milner C E, Davis I S and Hamill J (2005) Does free moment predict the incidence of tibial stress fracture? *Proceedings of the International Society of Biomechanics XXth Congress, XX*.

Milner C E, Davis I S and Hamill J (2005) Is dynamic hip and knee malalignment associated with tibial stress fracture in female distance runners? *Medicine and Science in Sports and Exercise* **37**, S346.

Seay J, Haddad J M, Milner C E, Davis I S and Hamill J (2005) Dynamic symmetry in female runners with a history of tibial stress fractures. *Proceedings of the International Society of Biomechanics XXth Congress, XX*.

Zifchock R A, Davis I and Hamill J (2005) Kinetic asymmetry in left and right dominant female runners: implications for injury. *Proceedings of the International Society of Biomechanics XXth Congress, XX*.

Zifchock R A and Davis I (2005) Kinetic Asymmetry in Female Runners With and Without Retrospective Tibial Stress Fractures *Medicine and Science in Sports and Exercise* **37**, S346.

From the data collected during the first four years, six abstracts were submitted and presented at the American College of Sports Medicine National Meeting in Indianapolis, Indiana and the American Society of Biomechanics Annual Meeting in Portland, Oregon. The references are provided below.

Davis, I., Milner, C. & Hamill, J. (2004). Does increased loading during running lead to tibial stress fractures? A prospective study. *Medicine and Science in Sports and Exercise*, 36, S58.

Davis, I.S., Milner, C.E. & Hamill, J. (2004). Prospective Study of Structural and Biomechanical Factors associated with the Development of Plantar Fasciitis in Female Runners. *Book of Abstracts 2004 American Society of Biomechanics Annual Meeting*, Portland, Oregon.

Dierks, T.A. & Davis, I. (2004). Lower extremity joint coupling and patellofemoral joint pain during running. *Medicine and Science in Sports and Exercise*, 36, S56.

Dierks, T.A., Davis, I.S. & Hamill, J. (2004). Lower extremity joint coupling in runners who developed patellofemoral pain syndrome. *Book of Abstracts 2004 American Society of Biomechanics Annual Meeting*, Portland, Oregon.

Milner, C., Davis, I. & Hamill, J. (2004). Is free moment related to tibial stress fracture in distance runners? *Medicine and Science in Sports and Exercise*, 36, S57.

Milner, C.E., Davis, I.S. & Hamill, J. (2004). Does sustaining a lower extremity stress fracture alter lower extremity mechanics in runners? *Book of Abstracts 2004 American Society of Biomechanics Annual Meeting*, Portland, Oregon.

From the data collected during the first three years, three abstracts were submitted and presented at the American College of Sports Medicine National Meeting in San Francisco, California, the XIXth International Society of Biomechanics Congress in Dunedin, New Zealand and the American Society of Biomechanics Annual Meeting in Toledo, Ohio. The references are provided below.

Ferber, R., McClay Davis, I., Hamill, J. & Pollard, C.D. (2003). Prospective biomechanical investigation of iliotibial band syndrome in competitive female runners. *Medicine and Science in Sports and Exercise*, 35, S91.

McClay Davis, I., Ferber, R., Hamill, J. & Pollard, C.D. (2003). Rearfoot mechanics in competitive runners who had experienced plantar fasciitis. *Book of Abstracts 2003 XIXth International Society of Biomechanics Congress*, Dunedin, New Zealand.

McClay Davis, I., Dierks, T.A., Ferber, R. & Hamill, J. (2003). Lower extremity mechanics in patients with patellofemoral joint pain: a prospective study. *Book of Abstracts 2003 American Society of Biomechanics Annual Meeting*, Toledo, Ohio.

From the data collected during years 1 and 2, three abstracts were submitted and presented at the American College of Sports Medicine National Meeting in St Louis, Missouri and at the World Congress of Biomechanics in Calgary Alberta, Canada. The references are provided below.

McClay Davis, I., Ferber, R., Dierks, T.A., Butler, R.J., & Hamill, J. (2002). Variables associated with the incidence of lower extremity stress fractures. *Book of Abstracts 2002 World Congress of Biomechanics*, Calgary, Alberta, Canada.

Ferber, R., McClay Davis, I., Hamill, J., Pollard, C.D., & McKeown, K.A. (2002). Kinetic variables in subjects with previous lower extremity stress fractures. *Medicine and Science in Sports and Exercise*, **34**, s25.

Pollard, C.D., & McKeown, K.A. Hamill, J., Ferber, R., McClay Davis, I. (2002). Selected structural characteristics of female runners with and without lower extremity stress fractures. *Medicine and Science in Sports and Exercise*, **34**, s991.

From the data collected during year 1, one abstract was submitted and presented at the American Physical Therapists' Association Combined Sections Meeting in Boston, Massachusetts. The reference is provided below.

Multiple Lower Extremity Stress Fractures In A Division I Cross Country Runner: A Case Study. Pollard C.D., McClay I.S., Hamill J. 2001 APTA Combined Sections Meeting, Boston, Massachusetts.

8) Presentations made

In addition to the conference presentations associated with the abstracts detailed above, the following presentations were made at the Center for Biomedical Engineering Research Symposium at the University of Delaware, Newark, Delaware in 2005.

Is Dynamic Hip and Knee Malalignment Associated with Tibial Stress Fracture in Female Distance Runners?

Milner, C.E., Davis, I.S. & Hamill, J.

In addition to the conference presentations associated with the abstracts detailed above, the following presentations were made at the Center for Biomedical Engineering Research Symposium at the University of Delaware, Newark, Delaware in 2004.

Lower extremity joint coupling and patellofemoral joint pain during running.

Dierks, T.A. & Davis, I.

Does sustaining a lower extremity stress fracture alter lower extremity mechanics in runners?

Milner, C.E., Davis, I.S. & Hamill, J.

In addition to the conference presentations associated with the abstracts detailed above, the following presentation was made in 2003.

Gait Retraining in Runners: An Application of the VICON Real-Time System

Presentation made to the Vicon Users' Group Meeting at the Gait and Clinical Movement Analysis Annual Meeting 2003, Wilmington, Delaware, Thursday May 8th, 2003.

9) Summary of information from the database

A summary of all the retrospective and prospective injury information we have collected is presented in tables 12 and 13. It is interesting to note the lower leg remains the most common site of retrospective injuries. Typically, the knee is the most common site of running injuries, with patellofemoral pain being the most common single injury at the knee. We feel this is because we initially advertised this study as a tibial stress fracture study and not as a running injury study. We have since changed this advertising strategy, and find that the difference is not as marked as in previous years.

In the prospective data, the injury pattern is more typical, with the knee being the most common site of injury and patellofemoral pain the second most common knee injury. Furthermore, the incidence of tibial stress fractures and tibial stress reaction is much reduced in the prospective database.

Table 12: Summary of retrospective injury information collected from the website database.

Injury Category	Incidence of Injury
Back TOTAL	36
Back sprain	3
Back strain	17
Disc pathology	2
Back other	14
Hip/ groin TOTAL	60
Gluteal strain/ tendinitis	4
Greater trochanteritis	11
Groin strain/ tendinitis	6
Pelvic stress fracture	5
Hip/ groin injury other	34
Thigh TOTAL	53
Femoral stress fracture	13
Hamstring strain	21
Quadriceps strain	13
Thigh other	6
Knee TOTAL	159
IT band friction syndrome	66
Lateral collateral strain	1
Medial collateral strain	3
Medial plica syndrome	1
Patellar tendinitis	14

Patellofemoral pain syndrome	41
Pes Anserinus tendinitis	3
Knee other	30
Lower leg	TOTAL
	211
Achilles tendonitis	23
Acute fibular fracture	4
Acute tibial fracture	2
Anterior compartment syndrome	6
Anterior tibialis strain	5
Fibular stress fracture	9
Gastroc/ soleus strain	6
Peroneal strain	8
Tibial stress fracture	48
Tibial reaction	71
Tibialis posterior strain	8
Ext. Digitorum in Longus Tendonitis	1
Posterior compartment syndrome	2
Lower leg other	18
Ankle	TOTAL
	79
Lateral ankle sprain	69
Medial ankle sprain	3
Ankle other	7
Foot	TOTAL
	129
Acute metatarsal fracture	3
Metatarsal stress fracture	23
Metatarsal stress syndrome	3
Neuroma	6
Painful 1 st MTP joint	2
Plantar fasciitis	47
Retrocalcaneal bursitis	1
Sesamoid fracture	3
Sesamoiditis	4
Foot other	28
Other, region unspecified	23
	TOTAL
	741

Table 13: Summary of prospective injury information collected from the website database.

Injury Category		Incidence of Injury
Back	TOTAL	33
	Back sprain	2
	Disc pathology	2
	Vertebral Fracture	1
	Back strain	12
	Back other	16
Hip/ groin	TOTAL	78
	Gluteal strain/ tendinitis	6
	Greater trochanteritis	7
	Groin strain/ tendinitis	9
	Hip/ groin injury other	53
	Pelvic stress fracture	3
	Hip other	53
Thigh	TOTAL	62
	Femoral stress fracture	8
	Hamstring strain	31
	Quadriceps strain	14
	Thigh other	9
Knee	TOTAL	152
	IT band friction syndrome	42
	Osteo-Arthritis	2
	Osgood-Schlatter's syndrome	2
	Lateral collateral strain	3
	Patellar tendonitis	17
	Patellofemoral pain syndrome	27
	Pes Anserinus tendinitis	6
	Knee other	50
Lower leg	TOTAL	112
	Achilles tendinitis	19
	Anterior compartment syndrome	5
	Anterior tibialis strain	5
	Fibular stress fracture	3
	Posterior Compartment Syndrome	1
	Gastroc/ soleus strain	14
	Peroneal strain	4
	Tibial stress fracture	8

Tibial stress reaction	12
Tibialis posterior strain	5
Acute fibular fracture	1
Lower leg other	36
Ankle	TOTAL
Lateral ankle sprain	26
Medial ankle sprain	8
Ankle other	12
Foot	TOTAL
Metatarsal stress syndrome	5
Metatarsal stress fracture	6
Painful 1 st MTP joint	4
Acute metatarsal fracture	7
Sesamoiditis	2
Neuroma	1
Plantar fasciitis	20
Retrocalcaneal bursitis	1
Tarsal Tunnel Syndrome	1
Sesamoid fracture	3
Foot other	41
Other, region unspecified	41
TOTAL	569

10) Degrees obtained that are supported by this award

Tracy Dierks was funded on this award and graduated from the University of Delaware with a PhD from the Department of Physical Therapy in May 2005.

Andrea Fidler was funded on this award and graduated from the University of Massachusetts with a Master of Science from the Department of Exercise Science in September 2003.

Christine Pollard was funded on this award and will graduate from the University of Massachusetts with a Ph.D. from the Department of Exercise Science in September 2003.

Reed Ferber was funded for a two-year Post-doctoral Research Fellowship and graduated from the University of Delaware in July 2003.

Kelly Anne McKeown was funded on this award and graduated from the University of Massachusetts with a Master of Science from the Department of Exercise Science in April of 2002.

11) Employment or research opportunities applied for and/ or received based on experience/ training supported by the grant

Clare Milner was funded for a two-year Post-doctoral Research Fellowship and has secured a faculty position in the Department of Exercise, Sport and Leisure Studies at the University of Tennessee in Knoxville, TN.

Tracy Dierks has secured a faculty position in the Department of Physical Therapy at Indiana University Purdue University in Indianapolis, IN.

Reed Ferber has secured a post-doctoral research fellowship in the Human Performance Laboratory at the University of Calgary, Alberta, Canada.

Christine Pollard is currently working as a post-doctoral research fellow at the University of Southern California.

Kelly Anne McKeown is currently working as the biomechanist in the Shriners' Hospital Motion Analysis Laboratory in Springfield, MA.

CONCLUSIONS

This Annual Report focused on the fifth year status of this investigation. Seven specific work objectives were outlined and discussed with respect to adherence and methods used to meet all objectives in a timely manner. We have now recruited 414 subjects and will continue to recruit subjects in the high risk subgroup of young, high mileage runners during a one year no-cost extension. We hope this will provide us with more prospective tibial stress fractures in the coming 12 months.

To date, data on 414 subjects have been collected and analyses performed on: retrospective tibial stress fractures; prospective tibial stress fractures; six subjects who had experienced a tibial stress fracture during the study and returned for reassessment of their running mechanics following recovery and a return to training; and seven control subjects who did not sustain any lower extremity bony injuries. In addition, six new conference abstracts were presented on tibial stress fractures, highlighting the wide spectrum of injuries that this database is providing valuable information about. Three manuscripts are in review for publication, one relating lower extremity mechanics to the incidence of tibial stress fracture, the second relating free moment of vertical ground reaction force to the incidence of tibial stress fracture and the third relating running mechanics to iliotibial band syndrome. An additional manuscript, investigating initial loading characteristics in relation to tibial stress fracture is planned for the coming year.

As with all prospective studies, the number of expected injuries can only be estimated. We expected to have approximately 20 tibial stress fractures at this point and only have 6. However, we have focused our recruitment in the past year to higher risk individuals, which we hope will yield more fractures. If this is not the case, we will likely pool our tibial stress reaction data (as proposed in the grant), along with the fibular stress fractures, which we believe likely have a similar mechanism of injury.

Overall, based on the retrospective data and preliminary prospective data, it appears that certain loading parameters such as loading rates, peak shock, and knee joint stiffness are related to the development of tibial stress fracture. Once we further validate these findings with additional data, we will be able to develop a simple, portable screening tool to predict those at increased risk for stress fractures. This would involve the use of a treadmill, accelerometer and laptop.

Once we are able to identify subjects at risk, we plan to develop interventions to reduce these risks. To this end, we have begun to develop protocols using realtime biofeedback to retrain gait patterns in order to reduce loading during running. This involves the same portable tool of a treadmill, accelerometer and laptop. We are in the process of testing these protocols through a number of case studies. Preliminary results are very promising and we believe this would be our next step in this line of research.

Our overarching goal is to reduce the risk of these serious and costly injuries to the military. We would propose to develop widespread screening throughout the military academies and ROTC programs. Once individuals are identified, they would be placed

into a gait retraining program with realtime feedback to teach them to reduce their loads during running. Large-scale, prospective epidemiologic studies would then be conducted to determine whether reducing excessive loads during running resulted in lowering the incidence of stress fractures.

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Appendix 1

Abstracts Presented at National and International Conferences.

1. INTRALIMB COORDINATION IN FEMALE RUNNERS WITH TIBIAL STRESS FRACTURES.
To be presented at the International Society of Biomechanics Annual Meeting, Cleveland, OH.
2. DOES FREE MOMENT PREDICT THE INCIDENCE OF TIBIAL STRESS FRACTURE?
To be presented at the International Society of Biomechanics Annual Meeting, Cleveland, OH.
3. IS DYNAMIC HIP AND KNEE MALALIGNMENT ASSOCIATED WITH TIBIAL STRESS FRACTURE IN FEMALE DISTANCE RUNNERS?
Presented at the American College of Sports Medicine National Meeting, Nashville, TN.
4. DYNAMIC SYMMETRY IN FEMALE RUNNERS WITH A HISTORY OF TIBIAL STRESS FRACTURES.
To be presented at the International Society of Biomechanics Annual Meeting, Cleveland, OH.
5. KINETIC ASYMMETRY IN LEFT AND RIGHT DOMINANT FEMALE RUNNERS: IMPLICATIONS FOR INJURY.
To be presented at the International Society of Biomechanics Annual Meeting, Cleveland, OH.
6. KINETIC ASYMMETRY IN FEMALE RUNNERS WITH AND WITHOUT RETROSPECTIVE TIBIAL STRESS FRACTURES
Presented at the American College of Sports Medicine National Meeting, Nashville, TN.

INTRALIMB COORDINATION IN FEMALE RUNNERS WITH TIBIAL STRESS FRACTURES

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INTRODUCTION

Tibial stress fractures are a common injury suffered by female runners. Studies looking at traditional kinematic or kinetic (such as ground reaction forces) differences between injured and uninjured populations during running have been unsuccessful at determining a causal factor associated with the injury [1]. The nature of differences that exist between groups may better be captured using dynamical systems techniques that capture the spatio-temporal dynamics of gait [2]. Dynamical systems analysis techniques have been shown to be more sensitive to subtle differences in human movement analyses. For example, gait variability as measured through continuous relative phase (CRP) has been shown to decrease in subjects with patellofemoral pain relative to an asymptomatic group [3].

The purpose of this study was to examine changes in gait variability in asymptomatic female runners who had previously suffered from a tibial stress fracture (TSF) compared to a control group (CTRL) of mileage matched female runners. It was hypothesized that the TSF group would have a significant difference in CRP variability between the stress fractured limb and the contralateral limb while the CTRL group would have no difference in CRP variability between limbs.

METHODS

Fifteen female runners with a unilateral retrospective tibial stress fracture and 15 mileage matched control subjects were recruited for this study. All volunteers were female, rearfoot strikers who ran at least 20 miles per week and were free of any lower extremity injuries at the time of data collection.

Subjects ran along a 25 m runway at a speed of 3.65 m/s ($\pm 5\%$). Three-dimensional kinematic data (120 Hz) were collected using a six-camera high-speed motion capture system. Five trials were collected for both the left and right limbs. For each subject, the profiles of the ankle, knee and hip sagittal view angles were interpolated to 100% of stance.

Bilateral hip, knee and ankle 3-D angles were calculated over each stride. Variability in intralimb coordination was assessed through measures of CRP for the hip-knee and knee-ankle coupling of both the involved and contralateral limb of the TSF subjects and the right and left limbs of the CTRL subjects. CRP variability was defined as the average standard deviation of CRP across each stride.

Effect size (ES) was calculated to express differences relative to the pooled standard deviation. Cohen (1988) proposed that ES values of 0.2 represent small differences; 0.5, moderate differences; and 0.8+, large differences.

RESULTS AND DISCUSSION

In the control group no effect was observed between the right and left limb in either the hip-knee or knee-ankle coupling ($ES < 0.1$). In the TSF group, CRP variability decreased in the involved limb relative to the contralateral limb in the hip-knee ($ES = .26$) and the knee-ankle coupling ($ES = .87$) (Figure 1).

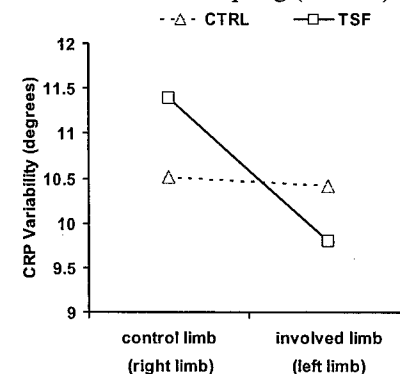


Figure 1: Mean CRP variability in the knee-ankle coupling for involved and contralateral limbs of TSF group and right and left limbs of the CTRL group.

Although the largest effect in the TSF group was observed in the knee-ankle coupling, a small effect was also observed in the hip-knee coupling, showing that a distal injury may also affect more proximal coordinative patterns. The results from both the TSF and CTRL groups support the hypothesis. It has been proposed that reduced CRP variability indicates a less flexible or less adaptable movement pattern [2, 3]. A less flexible pattern may exacerbate the injury or cause further injury to a TSF runner.

CONCLUSIONS

While the results of this study support the hypothesis that reduced CRP variability and thus less flexible/adaptable patterns are indicative of an injured condition, it is still not evident whether this less flexible pattern is a cause or a result of the injury.

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DOES FREE MOMENT PREDICT THE INCIDENCE OF TIBIAL STRESS FRACTURE?

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INTRODUCTION

Stress fracture injuries are common in distance runners, and occur most frequently at the tibia. Female runners are twice as susceptible to stress fracture as males. While multiple factors probably lead to the development of stress fractures, biomechanical factors such as loading are considered to play a role. Free moment (FM) is the torsional force about a vertical axis due to friction between the foot and the ground during stance. While FM has been linked to pronation, its potential role in running injuries has not been investigated widely. The relationship of FM to the loads experienced by the lower extremity makes it worthy of further investigation in relation to stress fracture injury. The spiral nature of some stress fractures indicates that torsional stresses on the lower extremity may be involved. If this is the case, the magnitude of the load may be more important than its direction. Furthermore, since FM is calculated directly from a force platform, it may have some value as a simple tool for predicting tibial stress fracture (TSF) in runners.

Preliminary work in our laboratory showed an increase in peak positive FM (resistance to toeing out), and trends towards higher FM at peak braking force and net angular impulse in 13 runners with a history of TSF, compared to runners with no previous lower extremity bony injuries. These trends suggest that there might be significant differences in FM variables between the groups if a larger subject pool were analyzed. Furthermore, the preliminary study did not consider the absolute magnitude of peak FM. An absolute measure (peak regardless of direction) may better represent the size of the torsional force acting on the lower extremity.

The purpose of this study was to investigate the relationships between FM variables and the occurrence of TSF in female distance runners. We hypothesized that maximum positive FM (POSFM), FM at peak braking force (FMBRAK), net angular impulse (IMP) and absolute peak FM (ABSFM) would be greater in runners with a history of TSF compared to uninjured controls. In addition, ABSFM would be predictive of group membership.

METHODS

A group of uninjured female distance runners with a history of tibial stress fracture ($n = 25$, age = 28 ± 10 y, weekly mileage = 116 ± 39 miles) and an age- and mileage-matched control group ($n = 25$, age = 26 ± 9 y, weekly mileage = 117 ± 47 miles) ran at 3.7m/s on a 25m runway containing a force platform sampling at 960Hz. Data from five trials were scaled to body weight and height and values for each variable averaged for statistical analysis. Differences between the TSF and control groups were examined using independent t-tests ($p \leq 0.05$). All t-tests were one-tailed, as only higher values in the TSF group were of interest. The utility of ABSFM in

predicting group membership was investigated using binary logistic regression.

RESULTS AND DISCUSSION

Generally, FM was greater in the TSF group (Table 1). While the magnitude of FM was significantly higher in the TSF group for POSFM and FMBRAK, the highest values in both groups were found in ABSFM. ABSFM also had a larger effect size (0.93, large) than POSFM (0.76, moderate). The higher value of ABSFM, compared to POSFM, indicates that in some runners negative FM (resistance to toeing in) is greater in magnitude than positive FM (resistance to toeing out). This is supported by our observations that some runners have a negative bias in their free moment curve. Therefore, POSFM does not always reflect the highest torsional force experienced by these subjects.

Further support for the importance of ABSFM in TSF was provided by the binary logistic regression. Regression results suggest that increased ABSFM is related to an increased likelihood of being in the TSF group. The model indicated that for every 1.0×10^{-4} increase in ABSFM, the likelihood of having a history of TSF increases by a factor of 1.354 (95% confidence interval 1.086 to 1.688), $p = 0.007$. According to the model chi-square statistic, the model is significant ($p = 0.001$). It also predicted group membership correctly in 66% of the cases. The Nagelkerke R square value was 0.251, suggesting that 25% of the variance between the two groups is explained by ABSFM.

These data suggest a relationship between FM and a history of TSF in distance runners. However, further prospective studies are needed to determine whether ABSFM can be used to predict the occurrence of TSF in female distance runners.

Table 1: Free moment variables in TSF and Control groups.

	POSFM	FMBRAK	IMP (s)	ABSFM
TSF	7.5 ± 4.5	4.0 ± 5.7	6.2 ± 5.7	9.0 ± 4.3
Controls	4.7 ± 2.5	1.6 ± 3.7	1.6 ± 5.5	5.9 ± 2.1
Effect size	0.76	0.49	0.83	0.93
P	0.023	0.043	0.781	0.001

All variables are $\times 10^{-3}$, except IMP which is $\times 10^{-4}$.

CONCLUSIONS

Peak positive FM, FM at peak braking force and absolute peak FM were significantly higher in the TSF group. This suggests an association with history of TSF in female distance runners. The magnitude of absolute peak FM successfully predicted a history of TSF in this group in 66% of cases.

ACKNOWLEDGEMENTS

This study was supported by Department of Defense grant DAMD17-00-1-0515.

Is Dynamic Hip and Knee Malalignment Associated with Tibial Stress Fracture in Female Distance Runners?

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It has been suggested recently that running injuries in females may be related to dynamic hip and knee malalignment in the frontal and transverse planes. Specifically, increased hip adduction (HADD), hip internal rotation (HIR) and knee abduction (KABD). Altered alignment of the lower extremity may predispose a runner to injury by changing load distribution. Since tibial stress fractures (TSF) are load-related injuries, differences in stance limb alignment may contribute to the risk of injury.

PURPOSE: To determine whether the occurrence of TSF is associated with dynamic malalignment of the hip and knee. It was hypothesized that runners who had sustained a TSF previously would exhibit increased HADD, HIR and KABD and altered axial rotation at the knee (KIR, KER), compared to runners with no history of fracture. The utility of foot abduction angle (FTLAB) as a simple surrogate measure of hip and knee malalignment was also tested.

METHODS: Healthy runners who had sustained TSF previously (n = 22) and an age and mileage matched control group (n = 22) participated. Gait data were collected at 120 Hz as subjects ran at 3.7m/s on a 25m runway. Data from five trials were averaged for analysis. Independent t-tests were used to investigate the hypothesized differences between the groups (one-tailed for HADD, HIR and KABD). **RESULTS:** (All values in degrees: adduction, internal rotation positive; abduction, external rotation negative.)

	HADD	HIR	KABD	KIR	KER	FTLAB
TSF	10.8	7.2	-5.7	4.3	-8.9	-5.0
Controls	7.4	7.4	-4.1	-0.6	-10.7	-4.1
p	0.03	0.47	0.03	0.01	0.35	0.62

These data support our hypotheses that runners with a history of tibial stress fracture have higher frontal plane HADD and KABD angles. In the transverse plane, only KIR shows an increase. Based on these data, dynamic hip and knee malalignment may play a role in stress fracture injuries in female runners. FTLAB does not differ between the groups, so is unsuitable as a simple surrogate measure of proximal joint alignment. **CONCLUSIONS:** HADD, KABD and KIR are increased in runners with a history of tibial stress fracture compared to a control group. Prospective studies are needed to determine whether increases in these angles during running are predictive of stress fracture injury.

DYNAMIC SYMMETRY IN FEMALE RUNNERS WITH A HISTORY OF TIBIAL STRESS FRACTURES

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INTRODUCTION

Change in gait symmetry, assessed using a variety of kinetic or kinematic measures, is observed across many pathologies affecting gait [1]. The observed asymmetries are typically viewed clinically as a pathological by-product of the affliction and efforts are expended to correct the asymmetry [2]. Newer research has however suggested that some degree of asymmetry is present in healthy non-afflicted individuals and may actually be functional [1]. Further, spatio-temporal symmetry measures derived from dynamical systems techniques, such as continuous relative phase (CRP), have been shown to change in locomotion based on the constraints of the task [3]. This past research suggests that changes in limb symmetry may not be a symptom of pathology, but rather a functional mechanism utilized by the body to cope with altered mechanical constraints caused by injury.

The purpose of this study was to examine changes in spatio-temporal gait symmetry in asymptomatic female runners who had previously experienced a unilateral tibial stress fracture (TSF) compared to a control group (CTRL) of mileage matched female runners. It was hypothesized that the TSF group would show increases in limb asymmetry compared to the CTRL group.

METHODS

Fifteen female runners with a unilateral retrospective tibial stress fracture (TSF) and 15 mileage matched control (CTRL) subjects were recruited for this study. All volunteers were female, rearfoot strikers who ran at least 20 miles per week and were free of any lower extremity injuries at the time of data collection.

Subjects ran along a 25 m runway at a speed of 3.65 m/s (\pm 5%). Three-dimensional kinematic data (120 Hz) were collected using a six-camera high-speed motion capture system. Five trials were collected for both the left and right limbs. For each subject, the profiles of the ankle, knee and hip sagittal view angles were interpolated to 100% of stance.

CRP was calculated bilaterally in the hip-knee and knee-ankle coupling of both groups. Spatio-temporal asymmetry was calculated as the difference in CRP patterns between involved and contralateral limb of the TSF subjects and the right and left limbs of the CTRL subjects in the hip-knee and knee-ankle couplings. Through these calculations, a time series about 0° indicates perfect spatio-temporal symmetry across the stance phase whereas deviations from zero represent a magnitude of asymmetry.

Effect size (ES) was calculated to express differences between groups relative to the pooled standard deviation. Cohen (1988) proposed that ES values of 0.2 represented small differences; 0.5, moderate differences; and 0.8+, large differences [4]. Effect sizes greater than 0.5 were considered clinically important.

RESULTS AND DISCUSSION

In both hip-knee (ES=0.52) and knee-ankle (ES=0.5) couplings moderate effects were seen between the TSF and CTRL group, where increases in asymmetry were seen in the TSF group (Figure 1).

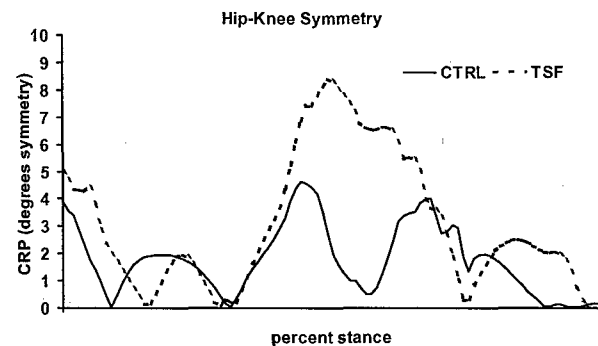


Figure 1: Between subject average of hip-knee CRP symmetry in both the stress fractured and control group.

Although effect sizes between groups were only moderate, it is interesting to note that all subjects were asymptomatic at the time of collection, showing that spatio-temporal asymmetry is present in female runners with a history of tibial stress fractures.

CONCLUSIONS

Female runners with a history of stress fractures show differences in spatio-temporal gait asymmetry compared to a healthy group. Although prospective studies are needed to determine whether this asymmetry is a cause or a result of the injury, this study adds to a growing body of literature that suggests gait asymmetry may be a functional adaptation utilized to cope with the injury.

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KINETIC ASYMMETRY IN LEFT AND RIGHT DOMINANT FEMALE RUNNERS: IMPLICATIONS FOR INJURY

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INTRODUCTION

The cause of running injuries continues to elude scientists. While a number of factors have been examined, the role of gait asymmetry and limb dominance has received little attention. Gait asymmetry has been suggested to be both a cause and effect of injury [1]. In addition, previous literature reports that left dominant (LD) people tend to be more symmetrical than right dominant (RD) people [2]. However, the relationship between laterality and gait has not been explored.

Therefore, one purpose of this study was to examine the differences in kinetic asymmetry during gait between LD and RD runners. The difference in injury patterns between LD and RD runners was also examined. The study focused on the symmetry of loading parameters that have previously been linked to chronic running injuries [3]. It was hypothesized that LD runners would be more symmetrical and, as a result, have fewer injuries than RD runners.

METHODS

This is an ongoing study in which, to date, there are 16 LD subjects and 16 age- and mileage-matched RD subjects enrolled. An *a priori* power analysis, based on a 10 point difference in symmetry and variability from previous literature, indicated that 24 subjects were needed per group. All volunteers were female, rearfoot strikers who ran at least 20 miles per week and were free of any lower extremity injuries at the time of data collection. Limb dominance was determined by the foot with which a subject would kick a ball.

Subjects ran along a 25 meter runway at a speed of 3.65 m/s ($\pm 5\%$), striking a force platform (Bertec Corp., Worthington, OH) at its center. Data were sampled at 960 Hz. Five trials were collected for both the left and right sides. The kinetic variables of interest were peak vertical impact ground reaction force, average and instantaneous vertical loading rates, and peak vertical shock. For each subject, these variables were extracted from the individual trials and averaged across the five trials, within each side.

The symmetry index (SI) [4] was used to evaluate the symmetry of each runner with respect to each of the kinetic parameters: $SI = (X_{dom} - X_{non-dom})/X_{dom} * 100$

Following the gait assessment, all running-related injuries were monitored for one year. Independent, two-tailed t-tests were performed to compare the kinetic variables and the number of injuries sustained by the LD and RD runners. A value of $p < 0.05$ was considered significant for all comparisons.

RESULTS AND DISCUSSION

While the SI values were not significantly different between the LD and RD runners (Table 1), instantaneous loading rate and peak shock were 24.9 and 32.5%, respectively, higher in the RD runners. These individuals also had 38.2% more injuries than LD runners. Based on the *a priori* power analysis, the current number of subjects does not adequately power the study. Therefore, the results may be strengthened as the study continues, and additional subjects are added.

In light of previous literature suggesting that LD people tend to be more symmetrical [5], the kinetic preliminary findings of this study are not surprising. LD people often cite the need to adapt to a "right-handed world." However, this has much less of an influence on lower extremity tasks. Therefore, the increased symmetry may not necessarily be a learned adaptation, but may be related to neurological control. The fact that the more asymmetrical, RD runners are so much more likely to become injured may lend insight into the role of symmetry in the mechanism of injury.

Future studies will focus upon examining how other gait mechanics (ie. kinematics) differ between LD and RD runners. The link between gait mechanics and the side on which a runner sustains an injury will also be studied.

Table 1: Comparison of SI Values and Number of Injuries between the LD and RD runners

	Impact GRF	Avg. LR	Instant. LR	Peak Shock	# of Injuries
LD	9.0	15.6	9.4	16.6	13
RD	8.0	17.1	12.5	24.6	21
p-value	0.68	0.69	0.30	0.22	0.26
% Diff	12.6	9.2	24.9	32.5	38.1

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Kinetic Asymmetry in Female Runners With and Without Retrospective Tibial Stress Fractures

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The tendency for a runner to become injured on a particular side is not well understood. It has been suggested that it may be due, in part, to asymmetry in their mechanics.

PURPOSE: The purposes of this study were (1) to compare the levels of kinetic asymmetry in runners who have previously sustained a tibial stress fracture (TSF) and those who have not (CON) and (2) to compare loading parameters between the involved and uninvolved sides of the TSF runners. It was hypothesized that the TSF group would be more asymmetric than the CON group and that they would exhibit greater loading on the involved side. **METHODS:** Twenty-five CON and 24 TSF subjects were eligible for this study. CON subjects reported to have never sustained a running injury. TSF subjects were included if they had sustained one or more tibial stress fractures on a single side of their body. Subjects were asked to run along a 25 meter runway at a speed of 3.65 m/s ($\pm 5\%$), striking a force platform (Bertec Corp., Worthington, OH) at its center. Data were sampled at 960 Hz. The speed was monitored with photoelectric cells placed 2.86 m apart. Five trials were collected for both the left and right sides. Any trials indicative of targeting were discarded. The same type of neutral running shoe was worn by each subject during data collection. Peak medial, lateral, braking, vertical impact, and vertical ground reaction forces, average and instantaneous vertical loading rates, and peak shock were measured in each subject. Symmetry Index (SI) was used to quantify asymmetry: $SI = (X_L - X_R) / 0.5 * (X_L + X_R)$. A 1-tailed, independent t-test was used to compare SI values between the TSF and CON groups. A 1-tailed, dependent t-test was used to compare loading values between the involved and uninvolved sides of the TSF group. **RESULTS:** SI values were not significantly different between the CON and TSF groups for any of the parameters. The peak vertical impact ground reaction force and peak shock were both significantly higher on the involved side in the TSF subjects ($p = 0.04$ and 0.02 respectively). **CONCLUSIONS:** These results indicate that while CON and TSF subjects have similar levels of asymmetry, those in the TSF group may have elevated loading values, bilaterally, that predispose them to injury.

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Appendix 2

Articles submitted for publication.

1. FREE MOMENT AS A PREDICTOR OF TIBIAL STRESS FRACTURE IN
DISTANCE RUNNERS.
Submitted to *Journal of Biomechanics*, May 2005.
2. BIOMECHANICAL FACTORS ASSOCIATED WITH TIBIAL STRESS
FRACTURE IN FEMALE RUNNERS.
Submitted to *Medicine and Science in Sports and Exercise*, February 2005.
3. RETROSPECTIVE BIOMECHANICAL INVESTIGATION OF ILIOTIBIAL
BAND SYNDROME IN COMPETITIVE FEMALE RUNNERS
Submitted to *American Journal of Sports Medicine*.

24 ORIGINAL ARTICLE

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27 **Free moment as a predictor of tibial stress fracture in distance runners.**

28
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48 Keywords: ground reaction forces, running, female

49 Word count: 2,637

50 **ABSTRACT**

51 Stress fractures are a common and serious overuse injury in runners, particularly female runners.
52 They may be related to loading characteristics of the lower extremity during running stance.
53 Some tibial stress fractures are spiral in nature and, therefore, may be related to torsional loads.
54 Free moment (FM) is a measure of torsional load at the interface with the shoe and ground.
55 Increases in FM variables may be related to a history of tibial stress fracture (TSF) in runners.
56 The purpose of this cross-sectional study was to investigate differences in FM between female
57 distance runners with and without a history of TSF and, additionally, to investigate the
58 relationship between absolute FM and the occurrence of TSF. A group of 25 currently uninjured
59 female distance runners with a history of TSF (28 ± 10 yr, 46 ± 15 km.wk⁻¹) and an age- and
60 mileage-matched control group of 25 healthy runners with no previous lower extremity fractures
61 (26 ± 9 yr, 46 ± 19 km.wk⁻¹) participated in this study. Ground reaction forces and foot placement
62 on the force platform were recorded during running at 3.7 m.s⁻¹ ($\pm 5\%$). Peak adduction, braking
63 peak and absolute peak FM and impulse were compared between groups using one-tailed t-tests.
64 The predictive value of absolute peak FM was investigated via a binary logistic regression. All
65 variables were greater in runners with a history of TSF. Absolute peak FM had a significant
66 predictive relationship with history of TSF. There is a significant relationship between higher
67 values for FM variables and a history of FM.
68

69 1. INTRODUCTION

70 Overuse injuries occur frequently in runners, with incidence rates as high as 85% being reported
71 in the literature (Bovens et al., 1989). The most serious overuse injury in terms of recovery time
72 is a stress fracture. Lower extremity stress fractures typically require six to eight weeks rest from
73 running to allow the bone to heal. Stress fractures are one of the five most common injuries in
74 the running population, accounting for between 6% and 14% of all injuries sustained by runners
75 (James et al., 1978; McBryde, 1985). The most commonly injured bone is the tibia, with tibial
76 stress fractures accounting for between 35% and 49% of all stress fractures in runners (Matheson
77 et al., 1987 and McBryde, 1985). There is also a gender bias in the occurrence of stress fractures,
78 with women reported consistently as being at twice the risk of sustaining stress fracture than men
79 (Arendt et al., 2003). Reasons for this gender bias are unclear: it may be partly related to lower
80 bone density or differences in bone geometry in females compared to males, although existing
81 studies are inconclusive (Beck et al., 2000; Bennell et al., 2004).

82

83 Recent studies of tibial stress fractures have suggested that their occurrence may be related to
84 higher loading of the lower extremity (Milner et al., 2005). Additionally, there is evidence that
85 some tibial stress fractures are spiral fractures (Spector et al, 1983). This suggests that, in
86 addition to vertical and shear forces, torsional forces may be involved in the development of a
87 tibial stress fracture (TSF). However, the frequency of occurrence of spiral TSF is unknown,
88 since they are usually classified according to their anatomical location on the tibia (Spector et al.,
89 1983). Furthermore, Ekenman et al. (1998) reported that the tibia is exposed to a combination of
90 bending, shearing and torsion simultaneously during activities such as running. The free moment
91 (FM) is the torsional force about a vertical axis due to friction between the foot and the ground

during stance (Holden and Cavanagh, 1991). While FM has been linked to pronation (Holden and Cavanagh, 1991), its potential role in running injuries has not been widely investigated. As an indicator of the torsional forces experienced at the point of contact between the foot and the ground, FM is worthy of further investigation in relation to stress fracture.

Preliminary work in our laboratory showed a higher peak adduction FM (resistance to toeing out) and trends towards greater FM at peak braking force and net angular impulse in 13 runners with a history of TSF, compared to runners with no previous lower extremity bony injuries (Milner et al., 2004). FM at peak braking force may be important if both shear and torsional forces are high at the same time. These trends suggest that there might be significant differences in FM variables between the groups if a larger subject pool were analyzed. Furthermore, the preliminary study did not consider the absolute magnitude of peak FM. Since this study indicated that some runners may have an abduction bias in FM (more than 50% stance with abduction FM), considering only their peak adduction FM would not indicate the greatest torsional force acting on their lower extremity. Therefore, an absolute measure (peak regardless of direction) may better represent the magnitude of the torsional force acting on the lower extremity.

The purpose of this cross-sectional study was to investigate differences in FM between female distance runners with and without a history of TSF and, additionally, to investigate the relationship between absolute FM and the occurrence of TSF. We hypothesized that maximum adduction FM (ADDFM), FM at peak braking force (FMBRAK), net angular impulse (IMP) and absolute peak FM ($|FM|$) would be greater in runners with a history of TSF compared to those

who had never sustained a lower extremity bony injury. In addition, we hypothesized that |FM| would be predictive of group membership.

2. METHODS

Subjects All subjects gave their written informed consent prior to participation in the study. All procedures were approved by the Institution's Human Subjects Review Board prior to the commencement of this study. Participants were recruited from local races, running clubs and teams. Subjects were excluded if they were currently injured, had abnormal menses (missed more than three consecutive monthly periods in the previous 12 months), were pregnant or suspected they were pregnant. A group of 25 currently uninjured female distance runners with a history of tibial stress fracture (28 ± 10 yr, 46 ± 15 km.wk⁻¹: TSF) and an age- and mileage-matched control group of 25 healthy runners with no previous lower extremity fractures (26 ± 9 yr, 46 ± 19 km.wk⁻¹: CTRL) participated in this study. The TSF group was an average of 48 ± 58 months post-injury. The majority (23/25) had one previous tibial stress fracture; one subject had two previous TSFs and another had four previous TSFs. *A priori* power calculations were based on data from a preliminary study conducted in our laboratory (Milner et al., 2004). Based on an α level of 0.05, β of 0.20 and effect sizes of 0.78 for FMBRAK and 0.48 for IMP, 24 subjects were needed to detect a two-fold difference between groups (Lieber et al., 1990). ADDFM was significantly different between groups in the preliminary study. On entry into the study, the TSF group had reported a previous tibial stress fracture, which had been confirmed by a medical professional and diagnostic imaging tests (bone scan, MRI or x-ray). All subjects were rearfoot strikers, having a strike index of ≤ 0.33 (Cavanagh and LaFortune, 1980). This was to ensure that they had a similar loading pattern, since there are differences in ground reaction force patterns between rearfoot, midfoot and forefoot strikers.

Experimental Protocol Ground reaction force data were collected at 960 Hz using a strain-gaged force platform (Bertec Corporation, Columbus, OH) as the subjects ran overground along a 23m runway at 3.7 m.s^{-1} ($\pm 5\%$). Running speed was monitored via two photocells placed 2.88m apart and linked to a timer. Footwear was standardized with all subjects wearing the same make and model of a commercially available neutral shoe. Data were collected for a single stance phase per trial, as the subject contacted the force platform located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change their gait or target the force platform were discarded. Prior to data collection, subjects performed practice trials to ensure that they would achieve the required speed and correct foot placement on the force platform without modifying their gait. Holden and Cavanagh (1991) noted differences between FM on the right and left sides of an individual. Therefore, foot contact on the force platform was on the involved side in the TSF group, to capture the appropriate FM data. Since neither side had a previous TSF in the CTRL group, there was no reason to prefer one side over the other; therefore, foot contact was made on the right side.

Kinematic data were collected, using a six camera motion capture system (Vicon, Oxford, UK) sampling at 120 Hz, for the calculation of strike index (Cavanagh and LaFortune, 1980). Retroreflective tracking markers were placed proximally and distally on the vertical bisection of the heel counter of the shoe and on the lateral part of the heel. In addition to marker position data collection during the running trials, a standing trial was collected with an additional anatomical marker placed on the tip of the toe box. This marker was used to determine the position of the long axis of the foot and its position and orientation in the global coordinate system during stance.

Data were processed using custom LabView programs (National Instruments Corporation, Austin, TX). FM is the torsional force about a vertical axis due to friction between foot and

ground during stance.. Following the sign convention of Holden and Cavanagh (1991), positive FM acts to resist toeing out (ADDFM) and negative FM acts to resist toeing in (ABDFM) (Figure 1). To preserve this sign convention, the FM calculation that follows was negated for the right foot. FM was calculated from the components of moment and force output from the force platform. FM is one of two components of the moment, M_z , acting about a vertical axis at the center of the force platform. The second component is the moment due to the resultant shear force acting through the center of pressure. Detailed examples of the relationship between FM and the moment about a vertical axis at the center of the force platform were provided by Holden and Cavanagh (1991). The equation describing the contributions of these two components to the vertical moment was used to derive FM from force platform output (Bertec Corporation, 2003). All force platform channels were baseline adjusted to a zero offset when unloaded prior to calculating FM.

$$FM = M_z - (CP_x \cdot F_y) + (CP_y \cdot F_x)$$

$$\text{where } CP_x = -M_y / F_z \text{ and } CP_y = M_x / F_z$$

where M_z was the moment about the z-axis, CP_x was the x-coordinate of center of pressure, F_y was the ground reaction force in y-direction, CP_y was the y-coordinate of center of pressure, F_x was the ground reaction force in x-direction, M_y was the moment about y-axis, F_z was the ground reaction force in z-direction, M_x was the moment about x-axis. Positive y-axis was in the direction of progression, positive z-axis was vertically downwards and positive x-axis was to the left when facing the direction of progression, following the right-hand rule. FM was normalized by dividing by body weight and height, making the reported FM dimensionless (and IMP in seconds). This reduces the effects of differences in weight and height between subjects on the magnitude of FM and facilitates meaningful comparisons between subjects.

Each variable was averaged over five trials per subject. ADDFM was the maximum adduction value of FM during stance; FMBRAK was the FM at peak braking force during stance; Impulse was the net area under the FM curve during stance; |FM| was the maximum absolute value of FM during stance.

Strike index was calculated as the position of the center of pressure at foot strike, relative to the long axis of the foot at foot flat. In the current study, it was determined by the point of intersection of a perpendicular from the center of pressure to the long axis of the foot. This position of this point along the long axis is calculated as a proportion of the overall length of the long axis away from the heel. Rearfoot striking is defined as a strike index ≤ 0.33 (Cavanagh and LaFortune, 1980). Strike index was determined using custom Visual Basic programs (Microsoft Corp) and Visual 3D software (C-Motion, Rockville, MD). All subjects were rearfoot strikers, with mean values for strike index of 0.08 ± 0.05 for the TSF group, and 0.09 ± 0.05 for the CTRL group.

Independent t-tests were used to test for significant differences between groups. Since we were only interested in whether the values of FM variables would be greater than normal in the TSF group, one-tailed tests were used. Lower values for FM variables in the TSF group were interpreted in the same way as no difference between groups.

A binary logistic regression was carried out to determine whether |FM| predicted group membership. The alpha level for all statistical tests was 0.05. In addition, effect sizes were determined for all variables, to aid the interpretation of any differences found. Ensemble average curves are also presented, both for the TSF and CTRL groups as a whole, and for subdivisions of subjects with adduction and abduction FM bias. FM bias was determined from the percent of stance with adduction FM for each subject. Subjects with adduction FM for more

than 50% of stance are designated as having a adduction FM bias and others as having a abduction FM bias. This subdivision of subjects was conducted to further explore whether |FM| was more appropriate than ADDFM as a representative FM variable.

3. RESULTS

All variables indicated that FM was greater in the TSF group (Table 1, Figure 2). While the magnitude of FM was significantly greater in the TSF group for both ADDFM and FMBRAK, the highest values in both groups were found for |FM|. |FM| also had a larger effect size (0.99) than ADDFM (0.80). The higher value of |FM|, compared to ADDFM, indicates that in some runners ABDFM (resistance to toeing in) is greater in magnitude than ADDFM (resistance to toeing out). Mean ABDFM was smaller than both ADDFM and |FM| and not different between the groups (TSF: 2.9 ± 4.3 ; CTRL: 2.9 ± 2.7), confirming that ABDFM was high in only a few subjects. There was no difference in IMP between the groups. The group average curves provide an indication of the general pattern of FM during stance (Figure 2), but as can be seen from the large spread indicated by the standard deviation in Table 1, the shape of the FM curve was quite variable between subjects. This is partly due to some runners having an abduction FM bias (7 in TSF and 9 in CTRL), illustrated in Figures 3 and 4.

Results of the binary logistic regression suggested that higher |FM| was related to an increased likelihood of being in the TSF group. The model indicated that for every 1.0×10^{-3} increment in |FM|, the likelihood of having a history of TSF increased by a factor of 1.365 (95% confidence interval 1.099 to 1.695, $p = 0.005$). According to the model chi-square statistic, the model is significant ($p = 0.001$). It also predicted group membership correctly in 66% of the cases. The

239 Nagelkerke R square value was 0.274, suggesting that 27% of the variance between the two
240 groups is explained by |FM|.

241

242 4. DISCUSSION

243 We investigated the differences in FM between female distance runners with a history of TSF
244 and those who had never sustained a lower extremity bony injury. Three of the four FM variables
245 compared between groups were greater in the TSF group. The largest effect size was found with
246 |FM| (although effect sizes of both |FM| and ADDFM were large). Higher values of |FM|
247 compared to ADDFM were found in both groups. Since ABDFM was smaller than ADDFM in
248 both groups, this indicates that in some runners, ABDFM was greater in magnitude than
249 ADDFM. We also observed that some runners have an abduction bias in their FM curve.
250 Therefore, ADDFM does not reflect the highest torsional force experienced by these subjects.
251 However, |FM| provides an indication of the peak magnitude of the torsional load acting on the
252 lower extremity in all runners. The higher FM values found in the TSF group suggest that higher
253 than normal torsional forces may be associated with tibial stress fracture. Since differences in
254 |FM| are larger than differences in ADDFM between groups, the magnitude of the torsional force
255 may be more important than its direction in relation to stress fracture injury.

256

257 The lack of significant difference between groups in IMP, despite a three-fold higher value in the
258 TSF group compared to the CTRL group, may be explained by the large spread within the data,
259 particularly in the TSF group. Some runners had a large positive FM, while others had a large
260 negative FM for most of the stance phase, and in others FM was small in magnitude for most of

261 the stance phase. As can be seen in the figures, there was a wide variation in the pattern of free
262 moment during the stance phase of running both within and between groups.

263
264 Furthermore, as is typical in ensemble curves, the peaks are attenuated relative to the individual
265 curves due to differences in the timing of peaks between subjects. Group average curves provide
266 an indication of the general pattern of FM during stance, but as can be seen from the large spread
267 indicated by the standard deviation in Table 1, this was quite variable between subjects. Due to
268 the bias of some runners in both groups towards abduction FM, there is a large spread in the
269 groups, particularly the TSF group. While there was no distinct pattern in the relative occurrence
270 of adduction and abduction FM bias between the two groups, inter-individual differences were
271 clear. Consequently, the mean ensemble average curves would be of limited interpretive value in
272 making comparisons with individuals, rather than between groups. In addition, since some
273 subjects have an abduction bias and others an adduction bias, the mean curve lies somewhere in
274 between these and does not represent either well. When the groups were subdivided by FM bias,
275 the resulting mean curves provided a more representative average curve.

276
277 The values for FM in the control group were somewhat similar to those reported in the literature
278 (Heise and Martin, 2001; Holden and Cavanagh, 1991). There was some variation between these
279 two studies, with the former reporting ADDFM 4.9×10^{-3} and the latter ADDFM of 9.7×10^{-3} .
280 Reported values for IMP were similar at 5.0×10^{-4} and 4.7×10^{-4} respectively. ADDFM for the
281 control group in the present study was similar to that reported by Heise and Martin (2001), but
282 IMP in the control group was lower than reported by these two groups. There are several
283 methodological differences between each of these two studies and the present study. Both

previous studies used male runners, whereas the present study used female runners. Gender differences in various biomechanical characteristics during running have been reported previously (Ferber et al, 2003). Furthermore, the runners tested by Holden and Cavanagh (1991) ran at a faster speed (4.5 m.s^{-1}) than either of the later studies (Heise and Martin, 2001 3.35 m.s^{-1} ; present study 3.7 m.s^{-1}). Speed has also been shown previously to affect the mechanics of running (Nilsson et al., 1985) and may, therefore, affect transmission of the torsional load to the lower extremity and the magnitude of the FM variables. The present study provides information about the characteristics of FM in normal female runners, as well as those with a history of TSF.

Further support for the importance of |FM| in TSF was provided by the binary logistic regression. The results of the binary logistic regression indicate that |FM| is a good predictor of a history of TSF. This suggests that |FM| may be a useful tool in screening for runners at risk of TSF. However, while a predictive relationship with previous TSF has been shown, it is beyond the scope of this cross-sectional retrospective study to determine whether |FM| is also higher in runners before they sustain a TSF. Further prospective studies are needed to determine the utility of |FM| in predicting future TSF in runners.

In conclusion, peak adduction FM, FM at peak braking force, impulse and absolute peak FM were significantly higher in runners with a history of TSF compared to a control group with no previous lower extremity bony injury. This suggests an association between higher FM and history of TSF in female distance runners. The magnitude of absolute peak FM successfully predicted a history of TSF in this group in 66% of cases.

307 **ACKNOWLEDGEMENTS**

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309

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348 **Figure 1:** Representation of adduction free moment resisting toe out and abduction free moment
349 resisting toe in of the foot during contact with the ground.

350

351 **Figure 2:** Average normalized free moment during stance in female runners with (TSF; dashed
352 line) and without (CTRL; solid line) a history of tibial stress fracture

353

354 **Figure 3:** Average normalized free moment during stance in female runners with a history of
355 tibial stress fracture. Heavy lines represent average values for subgroups with adduction (n=19;
356 solid) and abduction (n=6; dashed) free moment bias.

357

358 **Figure 4:** Average normalized free moment during stance in female runners without a history of
359 tibial stress fracture. Heavy lines represent average values for subgroups with adduction (n=14;
360 solid) and abduction (n=9; dashed) free moment bias.

361

362 **Table 1:** Average normalized free moment variables in female runners with (TSF) and without
363 (CTRL) a history of tibial stress fracture.

Figure 1

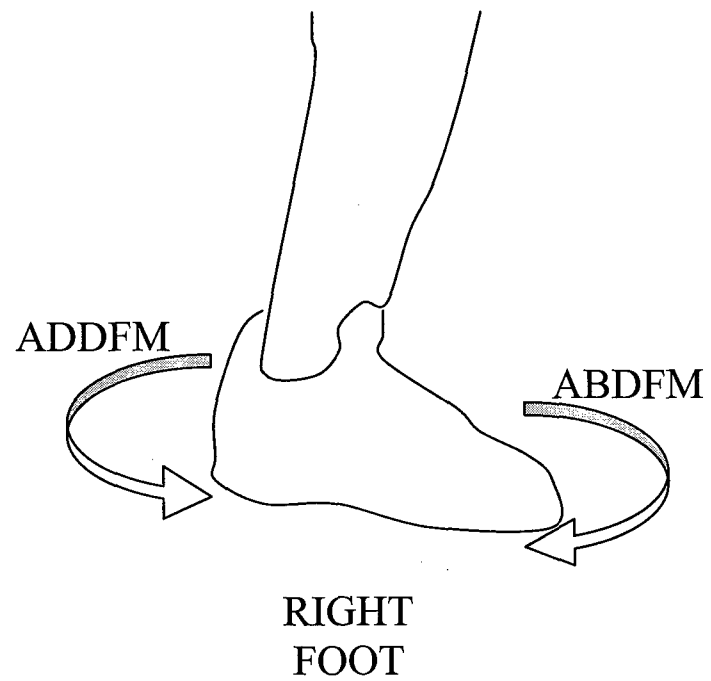


Figure 2

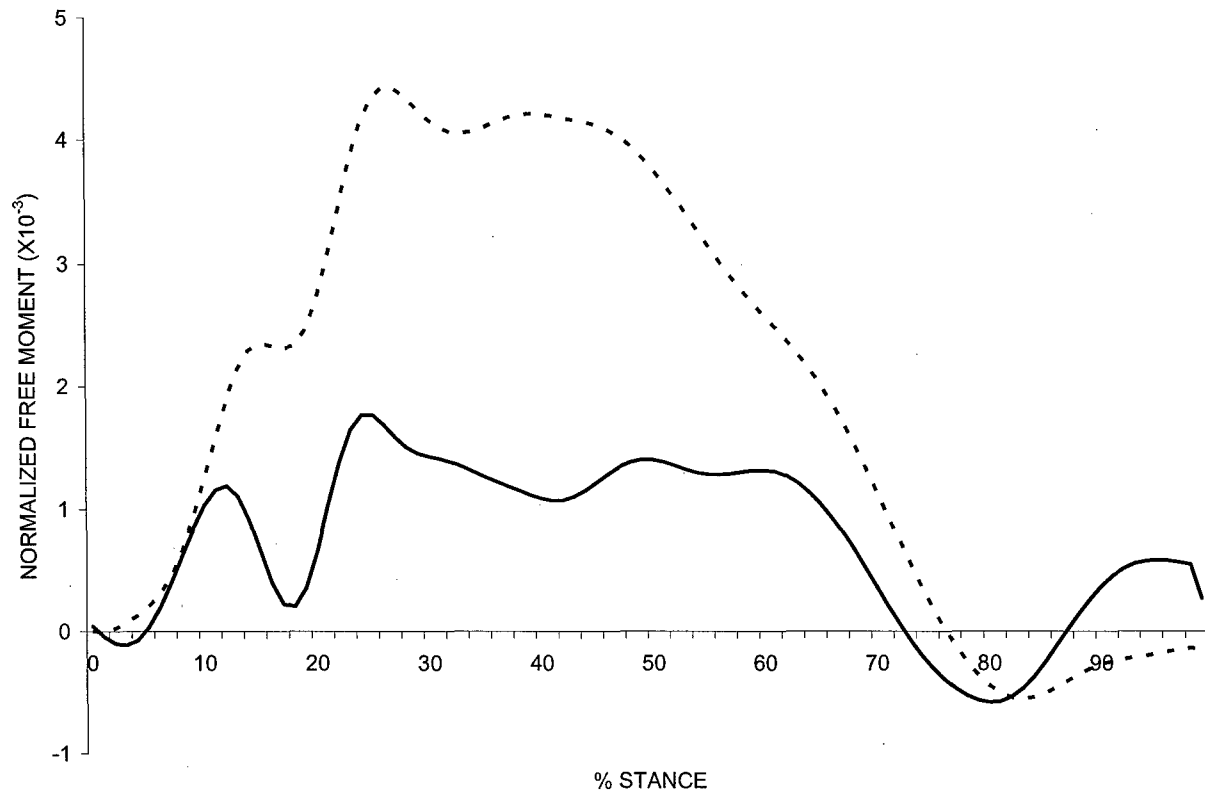


Figure 3

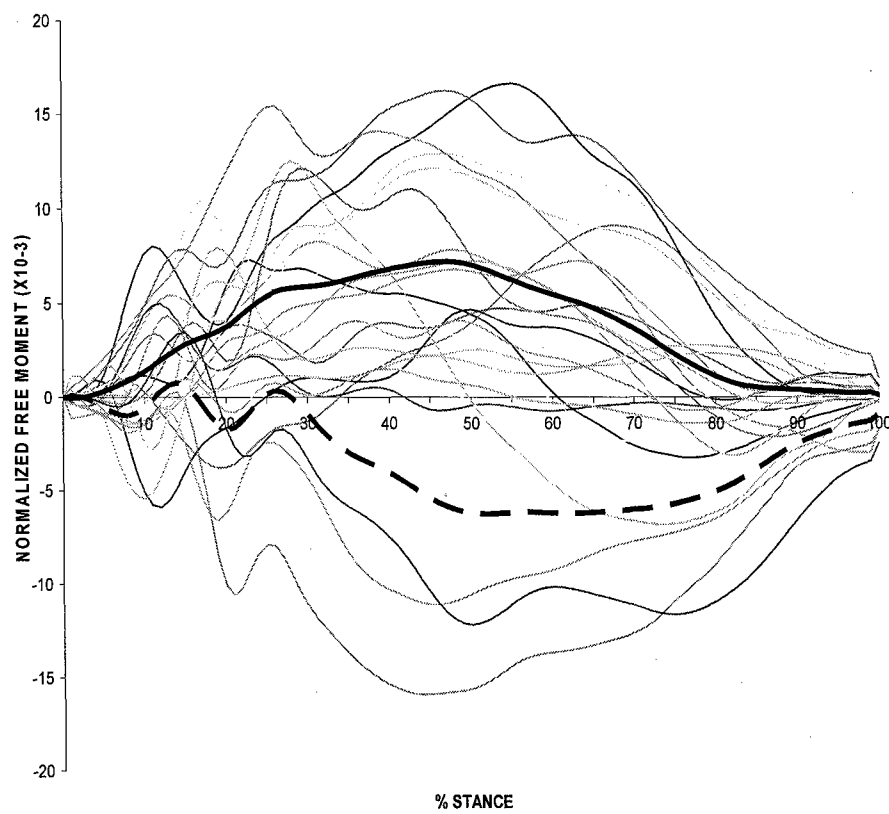


Figure 4

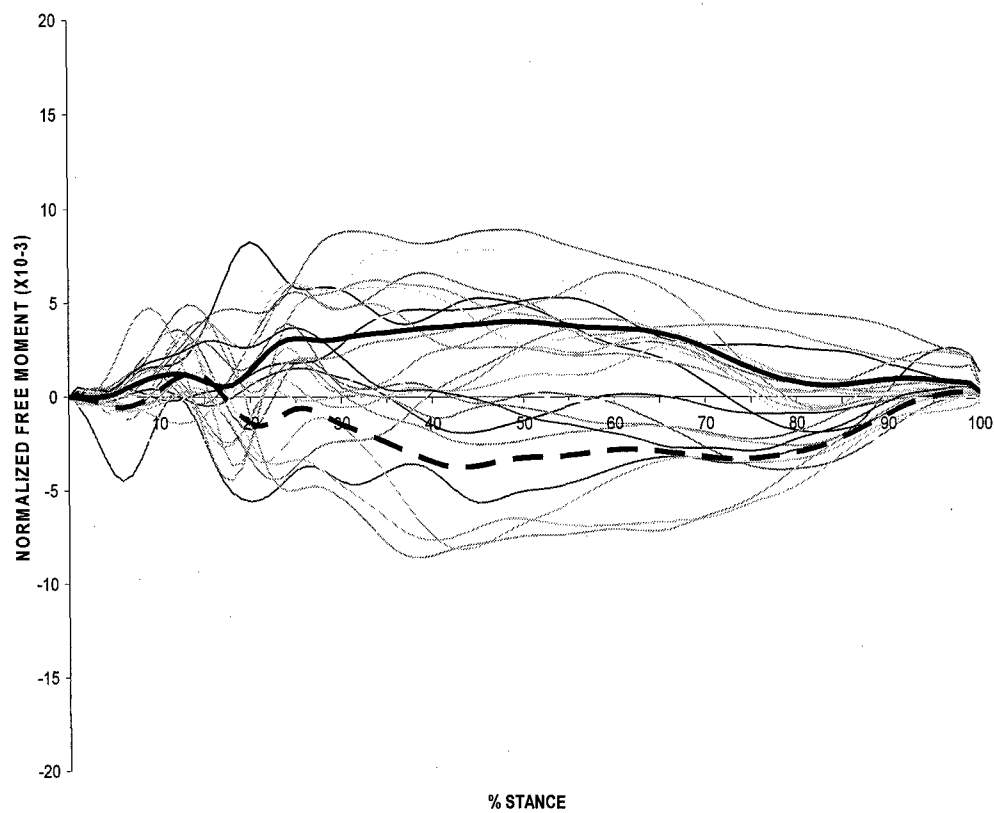


Table 1

	ADDFM	FMBRAK	IMP (s)	 FM
TSF	7.7 ± 4.7	4.6 ± 5.7	4.5 ± 9.9	9.3 ± 4.3
CTRL	4.7 ± 2.5	1.6 ± 3.7	1.6 ± 5.5	5.9 ± 2.1
Effect size	0.80	0.62	0.36	0.99
P	0.004	0.017	0.105	<0.001

All variables are $\times 10^{-3}$, except IMP which is $\times 10^{-4}$.

Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners

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ABSTRACT

Purpose: Tibial stress fractures are among the most serious running injuries, typically requiring six to eight weeks for recovery. The purpose of this cross-sectional study was to determine whether differences in structure and running mechanics exist between trained distance runners with a history of prior tibial stress fracture and those who have never sustained a fracture.

Methods: Female runners with a rearfoot strike pattern, aged between 18 and 45 years and running at least 32 km per week, were recruited for this study. Twenty subjects with a history of tibial stress fracture and 20 age and mileage matched control subjects with no previous lower extremity bony injuries participated in this study. Kinematic and kinetic data were collected during overground running at 3.7 m/s using a six camera motion capture system, force platform and accelerometer. Variables of interest were: vertical impact peak; instantaneous and average vertical loading rates; instantaneous and average loading rates during braking; knee flexion excursion; ankle and knee stiffness and peak tibial shock. Tibial varum was measured in standing. Tibial area moment of inertia was calculated from tibial x-rays for a subset of runners.

Results: The TSF group had significantly greater instantaneous and average vertical loading rates and tibial shock than the control group. The magnitude of tibial shock predicted group membership successfully in 70% of cases. **Conclusion:** These data indicate that a history of tibial stress fracture in runners is associated with increases in dynamic loading-related variables.

Keywords: ground reaction forces, kinematics, tibial shock, area moment of inertia

INTRODUCTION

Paragraph Number 1 Stress fractures are a common injury in runners. They are consistently among the five most common running injuries, and account for 50% of all injuries sustained by runners and military recruits (14, 15, 21). The overall incidence of stress fractures ranges from 1.5-31% (14, 15, 21, 24, 29). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (28). Similarly, the incidence of stress fractures in female college athletes was double that of males at a Division I institution (1). Others have reported an even greater gender bias in the incidence of stress fractures. An increased incidence of stress reactions, a precursor to stress fracture (9), by a factor of 2.91 in females compared to males has been reported in military recruits (29). The tibia is the most common site of stress fractures in runners accounting for between 33 -55% of total stress fractures reported (4, 10, 20, 28, 31).

Paragraph Number 2 Bone structure is thought to contribute significantly to the overall risk of tibial stress fractures. This has been shown to be the case in both male military recruits (24) and male runners (6), but not female runners (11). Medio-lateral tibial width (10) and tibial area moment of inertia (24) are smaller in those male military recruits who go on to develop a stress fracture. In addition, tibial cross sectional area, a strong determinant of area moment of inertia, is also smaller in male runners with a history of stress fracture (6). The relationship between tibial area moments of inertia and stress fracture has not been determined for female runners. However, tibial cross-sectional area was not linked to the occurrence of tibial stress fracture in a study of 13 female runners with a history of stress fracture (2).

Paragraph Number 3 Anatomic alignment has also been implicated in the etiology of lower extremity stress fractures. Matheson et al. (20) noted that varus mal-alignment (genu,

tibial, subtalar and forefoot varus) was often present in athletes with lower extremity stress fractures. During running, the body experiences vertical forces between 2.5 and 2.8 times body weight (25). During this compressive loading, a tibia in varus will likely experience greater bending moments as the vertical force vector projects medial to the tibial shaft. This may result in greater susceptibility to tibial stress fractures.

Paragraph Number 4 Stress fractures are thought to be related to some quantity, or "dose" of loading, where dose may be a measure of some combination of peak shock, ground reaction force loading rates, peaks and repetitions. However, some researchers have reported no difference in vertical impact and active peak ground reaction forces between runners with and without a history of tibial stress fracture (2, 6). Conversely, Grimston et al (11) reported significantly greater vertical impact and active forces in female runners with a history of tibial or femoral stress fractures compared to those without such a history. Increased ground reaction forces would likely result in greater bending moments experienced by the tibia. Furthermore, Hennig et al, (18) and Laughton et al. (17) both reported that vertical ground reaction force loading rates were significantly and positively correlated to peak tibial accelerations during running. Therefore, if loading rates are increased, it is likely that tibial shock is also increased. Whether the increased loading rates are directly related to strain rates experienced by the bone is yet to be determined. However, preliminary work in our laboratory (7) suggests that increased loading rates may be related to tibial stress fracture in female distance runners.

Paragraph Number 5 Although smaller in magnitude, anterior-posterior ground reaction forces applied to the lower extremity during the loading phase of stance may also influence loading of the tibia. Previous studies have again produced conflicting results. Runners with a history of tibial stress fracture have demonstrated increased (11) and normal (2,6) peak braking

force. Based on our preliminary work, which suggests that loading rates are significantly different between these groups with respect to vertical ground reaction forces (7), we expect loading rates during braking to also be increased in runners with a history of stress fracture.

Paragraph Number 6 The total range of motion the lower extremity undergoes during the loading phase of the gait cycle may influence the forces experienced by the body. Assuming a given impulse, greater excursions will likely result in lower peak ground reaction forces and possibly lower loading rates. McNitt-Gray et al. (23) demonstrated this principle by reporting that lower peak ground reaction forces and loading rates were associated with greater hip and knee flexion excursions in controlled landings in gymnasts. These increased excursions may, therefore, reduce one's risk for stress fractures. McMahon et al. (22) have shown that running with exaggerated knee flexion (Groucho running) reduces the effective vertical stiffness of the lower extremity and causes the runner to attenuate more shock between the shank and head, compared to normal running. Conversely, if knee joint excursion is decreased, greater lower extremity stiffness will likely result. A "stiff" runner has been shown to spend less time in contact with the ground (8) and attenuate less shock (22). This may also increase their risk of tibial stress fractures. The torsional stiffnesses of individual joints may provide additional insight into the differences between runners with and without a history of tibial stress fracture.

Paragraph Number 7 The purpose of this cross-sectional study was to determine whether differences in structure and mechanics existed between trained female distance runners with a history of a prior tibial stress fracture and those who had not sustained a fracture. We hypothesized that runners who had a prior tibial stress fracture would have increased vertical loading rates, increased vertical impact peak, increased loading rates during braking and increased knee and ankle joint torsional stiffness in the sagittal plane, compared to those who had

not sustained a fracture. Furthermore, we hypothesized that runners who had sustained a tibial stress fracture would have increased tibial acceleration and decreased knee flexion excursion, compared to those who had not sustained a fracture. Structurally, they would have increased tibial varum during standing and decreased tibial area moment of inertia. Additionally, we hypothesized that the magnitude of tibial shock would discriminate between runners with and without a history of tibial stress fracture.

METHODS

Paragraph Number 8 Subjects. Approval for all procedures was obtained from the Human Subjects Review Board of the University of Delaware prior to commencing this study. All subjects gave their written informed consent prior to participation in the study. Participants aged between 18 and 45 years who typically ran at least 32 km per week were recruited from local races, running clubs and university cross country teams by direct contact with study personnel or via flyers outlining the study. Subjects were excluded if they were currently injured, had a history of cardiovascular pathology, had abnormal menses (defined as missing more than three consecutive monthly periods in the last 12 months) or were pregnant or suspected they were pregnant. Runners with abnormal menses were excluded to reduce the likelihood of stress fractures being related to reduced bone density, rather than factors associated with running. Twenty rearfoot strikers with a history of tibial stress fracture (TSF: age 26 ± 9 y, 46 ± 11 km per week, 35 ± 28 months post-injury) and 20 age and mileage matched rearfoot striking control subjects with no previous lower extremity bony injuries (CTRL: age 25 ± 9 y, 47 ± 16 km per week) participated in this study. These data are part of a larger study of distance runners, and those with a rearfoot strike pattern, confirmed by calculation of the strike index (5), were

selected from the subject pool. On entry into the study subjects reported their injury history. The TSF group had reported a previous tibial stress fracture, which had been confirmed at the time by a medical professional using diagnostic imaging tests (bone scan, MRI or x-ray). Control runners had not reported any previous lower extremity bony injuries.

Paragraph Number 9 *A priori* power calculations for this study were done using preliminary data from our laboratory for peak tibial shock, instantaneous and average vertical loading rates and knee flexion excursion. Sample sizes were determined based on predicted power to detect a difference of 15% between the groups with an alpha 0.05 and 80% power. We consider a difference of 15% or more to be clinically relevant. Based on the formula of Lieber et al., (18), minimum sample sizes of between 9 and 20 subjects per group were determined from our existing data for these variables. Therefore, inclusion of 20 subjects per group should provide adequate power to detect clinically relevant differences in all variables between groups.

Paragraph Number 10 Kinematic and kinetic measurements. Lower extremity position data were collected at 120 Hz using a six camera Vicon 512 motion capture system (Oxford Metrics, Oxford, UK). Markers were placed on the lower extremity and pelvic region to enable three-dimensional kinematics to be determined for the stance phase of running. A Bertec force platform (Bertec Corporation, Columbus, OH) synchronized with the motion capture system was used to collect ground reaction force data at 960 Hz. Additionally, a uniaxial accelerometer (PCB Piezotronics Inc, Depew, NY), also sampling at 960 Hz, was attached over the anteromedial portion of the distal tibia, as described by Laughton et al. (17). Running velocity was monitored via two photocells linked to a timer.

Paragraph Number 11 Markers were attached at L5S1, iliac crest and anterior superior iliac spine to track the pelvic segment. Molded thermoplastic shells with four non-collinear

markers attached were secured on the postero-lateral proximal thigh and postero-lateral distal shank. Three markers were attached to the heel portion of the running shoe to approximate rearfoot motion: two marking the vertical bisection of the heel and a third on the lateral side of the heel. Several additional markers were attached to the subject initially to define the anatomical coordinate systems and inertial parameters of each segment. These markers were removed following the standing calibration trial. Anatomical markers were placed over the greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, first and fifth metatarsal heads and the tip of the toe box.

Paragraph Number 12 Subjects wore standard, neutral laboratory running shoes and ran overground along a 23m runway at a velocity of 3.7 m/s ($\pm 5\%$). Data were collected for a single stance phase as the runner traversed the force plate located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change their gait to target the force platform, as determined subjectively by the investigators, were discarded. Subjects performed practice trials to ensure that they could maintain a consistent running speed and make contact with the central portion of the force platform without modifying their gait.

Paragraph Number 13 Data were processed in Visual 3D (C-Motion, Rockville, MD). Three-dimensional ankle and knee angles were resolved about a Joint Coordinate System (12). Kinetic data, used in the calculation of joint stiffness, were calculated about XYZ rotation Cardan angles referenced to coordinate systems embedded in the distal segment. All other variables were calculated using custom LabView (National Instruments Corporation, Austin, TX) programs. Ground reaction force variables (vertical instantaneous and average loading rate (VILR, VALR), impact peak, (IPEAK) and anterior-posterior instantaneous and average loading

rates during initial braking (BILR, BALR) were determined. Loading rates were calculated between 20% and 80% of the period between footstrike and impact peak (vertical) or braking peak (anterior-posterior). This portion of the curve was chosen as it is the most linear portion of initial the loading part of the curve (Figure 1). Average loading rate was calculated as the total change in force divided by the total change in time over this period. Instantaneous loading rate was the peak sample-to-sample loading rate occurring during this period. Tibial shock (peak positive acceleration: PPA) was calculated after the average value and any linear trend in the acceleration signal were removed, as described by Shorten and Winslow (30). Peak positive acceleration was determined as the highest acceleration measurement during the stance phase. Knee flexion excursion (KEXC) was calculated as knee flexion range of motion from foot strike to peak knee flexion.

Paragraph Number 14 Joint torsional stiffnesses were calculated as the change in joint moment divided by the change in joint angle (8). It is recognized that these stiffness measures represent the sum of many individual stiffnesses and may, more accurately, be referred to as measures of quasi-stiffness (16). However, for the purposes of this paper, the term stiffness will be used. Sagittal plane average knee joint stiffness (KSTIF) was determined from foot strike to peak knee flexion (i.e. the loading phase) during stance (Figure 2). Sagittal plane average ankle joint stiffness (ASTIF) was determined from initial peak plantarflexion to peak dorsiflexion during stance (Figure 2).

Paragraph Number 15 Strike index was calculated to confirm that all subjects were rearfoot strikers, having a strike index $< 33\%$, as defined by Cavanagh and LaFortune (5). Strike index is described by the point of intersection of a perpendicular drawn from the point of center

of pressure at footstrike and the long axis of the foot. This point of intersection is reported as a percentage of foot length from the heel.

Paragraph Number 16 All variables were determined for each of five trials per subject, averaged within the subject and then averaged across groups.

Paragraph Number 17 Structural measurements Tibial x-rays were taken for a subset of 33 subjects (18 TSF and 15 CTRL). X-rays of both tibiae were taken from anterior and lateral views while standing with feet internally rotated 15° to account for the natural external rotation of the frontal plane of the tibia (24). A foot template was used to ensure consistency of foot placement between subjects. Tibial area moment of inertia (TIBAMI) was calculated from measurements made on the x-ray films, according to Milgrom et al. (24). As described by Milgrom et al. (24), the tibial cross-section was represented as an elliptical ring with an elliptical hole offset within it. Both the anterior-posterior and medial-lateral axes of rotation passed through the ring's centroid. Tibial varum was measured by an experienced physical therapist as the angle subtended by the bisection of the tibia in the frontal plane and a vertical reference.

Paragraph Number 18 Statistical analysis. Boxplots were used to identify outliers, defined as values more than 1.5 times the interquartile range away from the median. Identified outliers were removed from the data before statistical analysis of the differences between groups. A total of six data points fell outside this defined range and were removed as follows: two from the RTSF group for BALR, one from the CTRL group for ASTIF, one from each group for KSTIF and one from the CTRL group for TIBAMI. One-tailed independent t-tests were used to test for significant differences between groups, based on the directional hypotheses stated previously. Bonferroni adjustments for multiple comparisons were not made as the hypotheses tested were developed *a priori* and, therefore, should be considered independent of each other (27). A binary

logistic regression was carried out to determine whether PPA predicted group membership. The alpha level for all statistical tests was 0.05. We considered p values $0.05 < p \leq 0.10$ to be trends within the data. In addition, effect sizes were determined for all variables to aid in the interpretation of any trends found.

RESULTS

Paragraph Number 19 Instantaneous and average vertical loading rates were increased in the TSF group, compared to the control group (Table 1). There was also a trend towards a higher impact peak ($p = 0.057$, moderate effect size = 0.51) in the TSF group. However, loading rates during braking were not different between the groups. The TSF group also showed a large increase in peak tibial shock compared to controls. There was a trend towards higher knee joint stiffness in the TSF group ($p = 0.054$, moderate effect size = 0.54), but ankle joint stiffness was not greater in the TSF group (Table 2). Knee flexion excursion also showed no differences between the two groups. The structural measure tibial varum, was also not different between the groups. The decrease in tibial area moment of inertia in the TSF group was small and not significant. A posthoc power analysis indicated that the study was underpowered to detect a 9% difference in TIBAMI, the magnitude of the difference between groups found by Milgrom et al. (24). The effect size in the present study was the same as that reported by Milgrom et al. (24).

Paragraph Number 20 The results of the binary logistic regression suggest that increased PPA is related to an increased likelihood of being in the TSF group. The model indicates that for every 1g increase in PPA, the likelihood of having a history of TSF increases by a factor of 1.361 (95% confidence interval 1.020 to 1.816, $p = 0.036$). According to the model chi-square statistic, the model is significant ($p = 0.020$). It also predicts group membership correctly in 70% of cases.

The Nagelkerke R square value is 0.169, suggesting that 17% of the variance between the two groups is explained by PPA.

DISCUSSION

Paragraph Number 21 We investigated the biomechanical and structural differences between female distance runners with and without a history of tibial stress fracture. Runners with a history of tibial stress fracture exhibited greater instantaneous and average vertical loading rates, but no difference in loading rates during braking, compared to healthy controls. Differences in loading rates between these two groups have not been considered previously. Indications in our preliminary study (7) that both vertical and anterior-posterior loading rates are associated with a history of tibial stress fracture were only partially supported by this more comprehensive study. The small net differences in loading rates during braking between groups (BILR 6%, BALR 2%) account for their lack of association with a history of stress fracture. In terms of peak ground reaction forces, runners who had sustained a previous tibial stress fracture showed a small, non-significant (8% increase, $p = 0.057$) increase in the magnitude of the vertical impact peak compared to those who had never sustained a fracture. However, the moderate effect size (0.51) suggests that impact peak may be an important factor in the etiology of tibial stress fracture. While it is recognized that these are small increases, the cumulative effect of these slightly higher impacts in the TSF group may become important in injury development when repeated over thousands of foot strikes.

Paragraph Number 22 Based on our findings, tibial stress fractures, which are fatigue fractures of the bone, appear to be most related to loading rates. Loading rate is one of the factors associated with its fatigue limit. The fatigue limit of a tissue is related to the type of load applied,

its peak magnitude, loading rate and the total dose. When comparing these two groups of runners, the type of load is similar (a combination of compression and bending), as both groups were rearfoot strikers. The total dose was assumed to be similar, since the groups were matched for mileage, although this method did not account for differences in absolute number of steps due to the likely differences in stride length between subjects. The comparison of structure and alignment of the tibia also indicated that these were similar between the groups. Differences in load characteristics between the two groups were, therefore, likely to be reflected in the peak magnitude and loading rate. We hypothesized that both types of variables would be increased in the stress fracture group. However, our results, combined with those of Crossley et al. (6) and Bennell et al. (2), suggest that the differences lie in the vertical loading rate, rather than the impact peak or anterior-posterior loading rates during braking.

Paragraph Number 23 Peak tibial shock is another measure of the load applied to the lower extremity. Since a strong correlation has been reported between vertical loading rates and tibial shock (18), we expected that shock would also be increased in the TSF group. As expected, we found a large increase in tibial shock in the stress fracture group, alongside the increases in vertical loading rates. Additionally, tibial shock was found to predict a history of stress fracture in the binary logistic regression. While it is a surrogate measure of bone loading, tibial shock actually provides a more direct estimate of the load acting on the tibia itself than ground reaction forces. Ground reaction forces represent the net forces acting on the center of mass of the whole body (30). Therefore tibial shock may be a more sensitive discriminator of runners at higher risk of tibial stress fracture. While this needs to be confirmed with prospective studies, it may provide a means of screening for high-risk individuals. This measure is

particularly amenable to mass screening as there is minimal preparation time associated with its use, compared to a full kinematic and kinetic analysis of running gait.

Paragraph Number 24 The magnitudes of loading rates and peak tibial shock experienced during running are affected by the body's response to the applied load, as well as the magnitude of the load itself. The extreme example of Groucho running (22), in which the runner exaggerates knee flexion, provides a good illustration of this. When running with an extreme degree of knee flexion, the runner reduces the effective vertical stiffness of the lower extremity. The opposite is also true: running with reduced knee flexion increases the effective vertical stiffness of the lower extremity. We had expected to find significantly greater knee and ankle joint stiffness, accompanied by reduced knee joint excursion, in the TSF group. However, this was not supported by our results, which indicated only a trend towards increased knee stiffness in the TSF group ($p = 0.054$) for a 9% increase. However, the effect size was moderate (0.54), indicating that stiffness may be an important factor. There was no difference in excursion between the groups.

Paragraph Number 25 The decrease in TIBAMI in the TSF group was small, but showed the same small effect size (0.34) as found in 295 male infantry recruits who sustained a stress fracture during basic training (24). These recruits had a statistically smaller TIBAMI than those who did not fracture (24). However, in another study, several measures of tibial geometry showed no difference from normal in a group of 13 female runners with a history of tibial stress fracture (2). It remains inconclusive whether decreases in TIBAMI are related to a history of tibial stress fracture in female distance runners. Furthermore, tibial varum was no different between groups. This was unexpected, as Matheson (20) noted that varus mal-alignment was often present in male and female athletes with a history of stress fracture. We found that, in

female distance runners, dynamic biomechanical characteristics of running gait associated with vertical loading show the greatest differences between groups.

Paragraph Number 26 The standardization of running speed and footwear reduces the number of extraneous variables contributing to differences between subjects during the laboratory-based comparison of running mechanics. However, during the follow-up period, footwear and running speed were not monitored. This is a limitation of the study because the running mechanics recorded in the laboratory may differ slightly from those that the subject experiences during normal running. Differences in footwear and running speed may affect the magnitude of lower extremity loading experienced. Furthermore, the conclusions drawn from this study should be interpreted with caution because the study was retrospective and cross-sectional. Prospective studies of runners who sustain a tibial stress fracture are needed to determine cause and effect with respect to loading rates and fracture occurrence.

Paragraph Number 27 In conclusion, based on the results of this study, a history of tibial stress fracture in female runners is associated with increases in several dynamic loading-related variables: instantaneous and average vertical loading rate and peak tibial shock. A trend toward higher knee stiffness and impact peak, indicated by a moderate effect size for history of tibial stress fracture, but not statistically significant differences, was also found. There were no significant differences in the structural measures of tibial area moment of inertia and tibial varum angle in this group of runners with a history of tibial stress fracture compared to a healthy control group. The magnitude of peak tibial shock predicted group membership successfully in 70% of cases.

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Figure 1: Instantaneous and average vertical loading rates were calculated over the portion of the vertical ground reaction force curve between 20% and 80% of the time to impact peak. See text for full description.

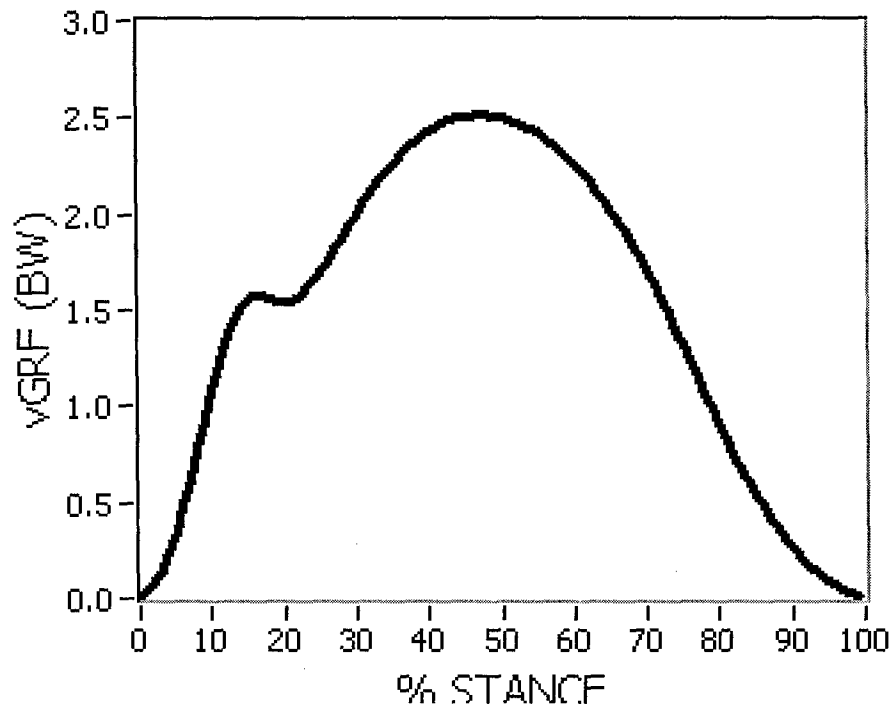


Figure 2: Illustration of the calculation of average sagittal plane joint stiffness, depicting the ankle joint. See text for full description.

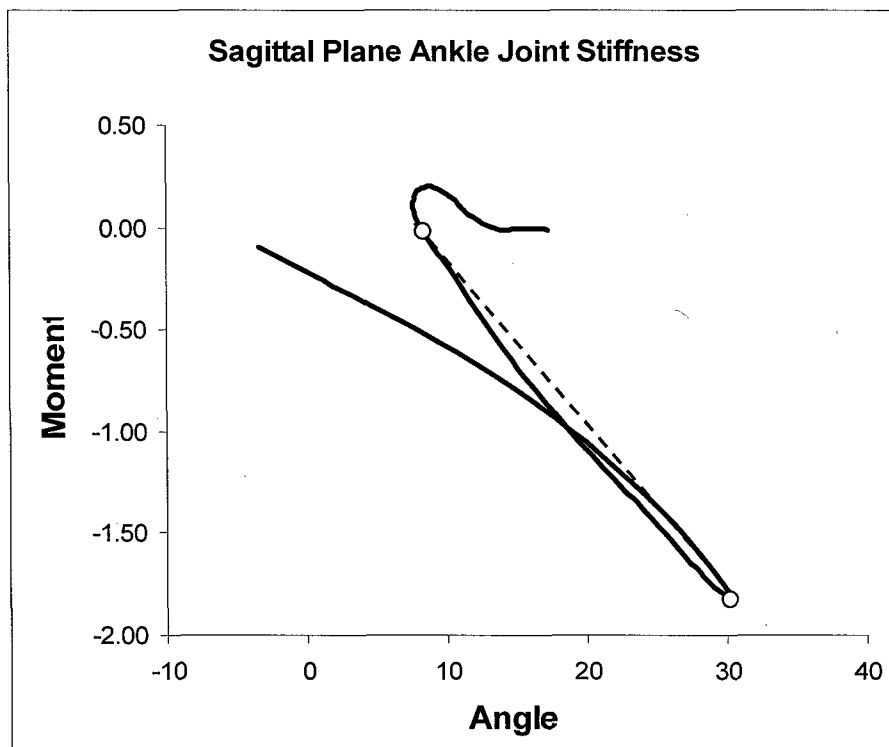


TABLE 1. Mean (SD) ground reaction force variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group.

Ground Reaction Force	TSF	CTRL	Effect size	p value
IPEAK (BW)	1.84 (0.21)	1.70 (0.32)	0.51	0.057
VILR (BW.s ⁻¹)*	92.56 (24.74)	79.65 (18.81)	0.59	0.036
VALR (BW.s ⁻¹)*	78.97 (24.96)	66.31 (19.52)	0.56	0.041
BILR (BW.s ⁻¹)	20.35 (6.17)	19.29 (4.70)	0.19	0.272
BALR (BW.s ⁻¹)	8.54 (3.10)	8.37 (2.25)	0.07	0.420

* Significant at $p \leq 0.05$.

Table 2: Mean (SD) joint excursion, stiffness and structural variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group.

	TSF	CTRL	Effect size	p value
KEXC	33.1 (5.0)	34.8 (5.2)	0.34	0.147
ASTIF (x10 ⁻²)*	4.31 (0.59)	4.59 (0.61)	-0.46	-^
KSTIF (x10 ⁻²)	4.88 (0.88)	4.46 (0.68)	0.54	0.054
PPA*	7.70 (3.21)	5.81 (1.66)	0.74	0.014
TIBAMI	11312 (2883)	12224 (2387)	-0.34	0.174
TIBVAR	6 (2)	6 (2)	-0.36	0.128

* Significant at $p \leq 0.05$. ^ In opposite direction to hypothesized difference.

RETROSPECTIVE BIOMECHANICAL INVESTIGATION OF ILIOTIBIAL BAND
SYNDROME IN COMPETITIVE FEMALE RUNNERS

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ABSTRACT

Purpose: To examine differences in running mechanics between runners who had previously sustained iliotibial band syndrome (ITBS) and runners with no knee-related running injuries.

Methods: The gait mechanics of 22 females who had been diagnosed with ITBS were compared to 22 age, mileage, and limb matched healthy females during running. Comparisons of hip and knee 3-D joint angles, angular velocities, and moments during the stance phase of running gait were made.

Results: No significant differences between groups were observed for the frontal plane rearfoot or transverse plane knee or hip variables of interest. The ITBS group exhibited a trend towards greater peak hip internal rotation angle a significantly greater peak hip adduction angle compared to the control group.

Conclusions: Female recreational runners who had previously sustained ITBS exhibited greater hip frontal and transverse plane motions during running compared to controls. These data may may explain how, overtime, atypical running mechanics can lead to lower extremity musculoskeletal injuries such as ITBS.

Key Words: Iliotibial band syndrome, Running mechanics, Kinematics, Kinetics

INTRODUCTION

Iliotibial band syndrome (ITBS) is one of the most common injuries runners sustain (Taunton, 2002). Repetitive friction of the ITB over the lateral femoral epicondyle can lead to inflammation, hyperplasia, fibrosis, and mucoid degeneration observed as pain associated with ITBS (Nemeth et al., 1996). Orchard et al. (1996) suggested that the ITB experiences the greatest amount of friction with the lateral femoral epicondyle near 30° of knee flexion which is observed during the first half of the stance phase of running.

The iliotibial band (ITB) functions as an anterolateral knee stabilizer and as a hip abductor (Frederickson et al., 2000). It has been reported that runners with ITBS exhibited significantly weaker hip abductor muscle strength in the affected limb compared to the unaffected limb and healthy controls (Frederickson et al., 2000). The primary adductor of the hip is the gluteus medius, which also acts as an external rotator, and the tensor fascia latae (Moore, 2003). Thus, weakness of these muscles would suggest that runners with ITBS may exhibit greater hip adduction and internal rotation during the stance phase of running.

It has been suggested that excessive rearfoot motion can influence knee mechanics and contribute to running-related injuries such as patellofemoral pain and ITBS (Duffey et al., 2000; Hamill et al., 1999; Williams et al., 2003). Greater amounts of rearfoot motion are likely to influence knee motion due to the coupling that has been shown to occur in the lower extremity (Lundberg, 1989; Inman, 1976). During the first half of the stance phase, the calcaneus everts and the head of the talus internally rotates (Lundberg, 1989; Inman, 1976). The tibia internally rotates with the talus due to the tight articulation of the ankle joint mortise. Therefore, chronic and excessive amounts of rearfoot eversion could result in greater knee internal rotation and potentially be associated with the etiology of ITBS.

Previous studies suggest that the etiology of ITBS may be related, in part, to atypical running mechanics. However, few studies have performed a comprehensive analysis of these variables. Thus, the purpose of this study was to examine differences in running mechanics between female runners who had previously sustained ITBS compared to runners with no knee-related running injuries. It was hypothesized that the ITBS runners would exhibit greater hip adduction and internal rotation, knee internal rotation, and rearfoot eversion peak angles, peak angular velocity and peak joint moments compared to the control group.

METHODS

Subjects

A priori power analyses ($\beta=0.20$; $P=0.05$) were conducted based on pilot data (Ferber et al., 2003) and a minimum of 14 subjects per group were found to be necessary for statistical significance. The subjects involved in this study ($n=44$) were part of a larger ongoing prospective investigation of female running injuries ($n=400$). As part of the larger study, all previous lower extremity injuries for all participants were recorded. The database was then examined and 22 females who had been diagnosed with ITBS by physician and/or a licensed physical therapist were chosen for analysis for this study. Twenty-two age, mileage, and limb matched females with no previous knee-related musculoskeletal injuries were then chosen for the control group. The age, mean body mass, and body height of the ITBS subjects were 35.47 years (SD 10.35 years), XXkg (SD XXkg), and XXm (SD XXm), respectively and the control subjects were 31.23 years (SD 11.05 years), XXkg (SD XXkg), and XXm (SD XXm), respectively. All subjects were free of any obvious lower extremity malalignments or injuries at the time of data collection. Prior to participation, each subject signed a consent form approved by the University's Human Subjects Compliance Committee.

Procedures

Retro-reflective markers for tracking three-dimensional movement were placed on the thigh, shank, pelvis, and rearfoot (Figure 1). Anatomical markers defining the joint centers were placed over the following locations: bilateral greater trochanters, medial and lateral femoral condyle, medial and lateral malleoli, heads of the 1st and 5th metatarsals. After a static standing calibration was collected, the anatomical markers were removed and dynamic trials were

collected. Subjects ran along a 25m runway at a speed of 3.65 m/s ($\pm 5\%$) striking a force plate at its center. Running speed was monitored using photoelectric cells placed 2.86 m apart along the runway. Five running trials were collected for the right lower extremity during stance.

Insert Fig. 1 about here

Data collection and analysis

Kinematic data were collected with a passive, 6-camera, 3-D VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK). The cameras were calibrated to a volume of 2.0 m³ and calibration errors were all below 3 mm. Kinematic data were sampled at 120 Hz and low-pass filtered at 8 Hz with a fourth-order zero lag Butterworth filter. Kinetic GRF data were collected using a force plate (BERTEC Corp, Worthington, OH, USA). GRF data were collected at 960 Hz and low-pass filtered at 50 Hz with a fourth-order zero lag Butterworth filter. Trials were normalized to 100% of stance and five were averaged for each subject.

Visual3D software (NIH Biomotion Laboratory, Bethesda, MD, USA) was used to calculate kinematic and kinetic variables. All lower extremity segments were modeled as a frustra of right cones model and anthropometric data provided by Dempster (1959). The kinematic and kinetic variables of interest were extracted from individual trials.

Statistical design

The kinematic and kinetic variables of interest were selected from the first 60% of the stance phase of gait and included ankle and knee joint 3D peak angles, peak angular velocities, and peak moments. Specific biomechanical variables of interest were 1) rearfoot peak eversion angle, excursion, and velocity, and inversion moment, 2) knee peak internal rotation angle and velocity and external rotation moment, and 3) hip peak internal rotation angle and velocity and

internal rotation moment, and 4) hip peak adduction angle and velocity and abduction moment. Variables were statistically compared using one-way ANOVAs at a confidence level of 0.05. Tukey post-hoc tests were performed where appropriate.

RESULTS

Table 1 presents a summary of kinematic and kinetic comparisons of the variables of interest for the ITBS injured and non-injured and the control group's matched limb. No significant differences were observed for the frontal plane rearfoot or transverse plane knee variables of interest (Table 1). No significant differences were observed for transverse plane hip variables although the ITBS group exhibited a trend towards greater peak hip internal rotation angle compared to the control group (Table 1). In the frontal plane, the ITBS group exhibited a significantly greater peak hip adduction angle compared to the control group (Table 1).

Table 1: Mean (SE) and *P*-value for the ITBS non-injured and previously injured limb compared to the control (CON) group for the selected variables of interest.

Joint	Variable of Interest	ITBS Injured	CON	<i>P</i> -value
Rearfoot	Ev Excursion (deg)	13.16 (0.96)	14.00 (1.13)	0.57
	Peak Ev Angle(deg)	9.54 (0.61)	9.19 (0.85)	0.74
	Peak Ev Vel (deg/s)	182.95 (14.36)	216.07 (18.11)	0.16
	Peak Inv Mom (Nm/kg)	-0.16 (0.03)	-01.5 (0.03)	0.69
Knee	Peak Int Rot Angle (deg)	1.39 (1.38)	1.37 (1.40)	0.99
	Peak Int Rot Vel (deg/s)	151.26 (9.42)	163.22 (17.00)	0.54
	Peak Ext Rot Mom (Nm/kg)	-0.09 (0.01)	-0.10 (0.02)	0.50
Hip	Peak Int Rot Angle (deg)	11.60 (3.37)	5.88 (0.92)	0.09
	Peak Int Rot Vel (deg/s)	86.03 (10.51)	105.56 (11.51)	0.22
	Peak Int Rot Mom (Nm/kg)	0.38 (0.02)	0.38 (0.03)	0.97
	Peak Add Angle (deg)	10.98 (1.26)	7.08 (1.03)	0.02 *
	Peak Add Vel (deg/s)	148.31 (12.57)	153.33 (11.17)	0.76
	Peak Abd Mom (Nm/kg)	-1.37 (0.05)	-1.45 (0.06)	0.22

* indicates CON different than ITBS non-injured limb

DISCUSSION

The purpose of this study was to examine differences in running mechanics between runners who had previously sustained ITBS and runners with no knee-related running injuries. There is a paucity of literature related to running mechanics and the etiology of ITBS in runners. Of those studies, few studies have comprehensively examined how atypical running mechanics may be related to the etiology of ITBS.

In support of the hypothesis, the ITBS group exhibited a trend towards greater peak hip internal rotation angle and a significantly greater peak hip adduction angle for the previously injured limb compared to the control group. These results support those of Fredrickson et al. (2000) who reported that runners with ITBS exhibited significantly weaker hip abductor muscle strength in the affected limb compared to healthy controls. It seems likely that weakness of the hip adductor muscles (gluteus medius and tensor fascia latae) would result in greater hip adduction and internal rotation during the stance phase of running. It is also possible that repetitive exposure to greater hip adduction and internal rotation may necessitate greater passive restraint from the ITB and, overtime, result in the development of ITBS. However, prospective studies are necessary to better determine the role of excessive hip joint frontal and transverse plane motion and ITBS.

It has been postulated that known differences in structure may predispose females to differences in running mechanics which, over many repetitions, may lead to specific injuries. Female recreational runners twice as likely to sustain ITBS as compared to their male counterparts (Taunton et al, 2002). Ferber et al. (2003) suggested that female recreational runners exhibited a greater peak hip adduction and internal rotation angle compared to male runners possibly as a result of greater hip width to femoral length ratio and greater active hip

internal rotation range of motion, respectively (Horton & Hall, 1989; Simoneau et al., 1998). While not measured in the current study, the greater peak hip adduction and internal rotation angle observed in the ITBS group may be linked to differences in anatomical structure and range of motion compared to the control group. Studies determining how anatomical structure and gait mechanics are necessary to better determine this association.

Contrary to the hypotheses, there were no differences in any rearfoot frontal plane or knee transverse plane variables of interest. Other studies have suggested that greater amounts of rearfoot eversion can lead to increased knee rotation and possibly contribute to the development of certain lower extremity injuries such as ITBS (McClay and Manal, 1997; Nigg et al., 1993; Nawoczenski et al., 1998; Williams et al., 2001). Pilot data based on a group of prospective ITBS injured subjects showed that greater peak rearfoot eversion and knee internal rotation angles were observed compared to healthy controls (Ferber et al., 2003). However, results from the current study suggest that rearfoot and knee mechanics are not different between runners who have previously sustained ITBS and healthy controls.

There are factors which may have influenced the results of this study. The study is retrospective in nature. Therefore, it is difficult to draw conclusions between running mechanics and the etiology of ITBS. Secondly, the ITBS runners were healthy at the time of testing so true differences between the two groups may be masked. Third, it is possible that inclusion of more subjects may have resulted in statistical significance for some of the comparisons. However, a sample size estimate indicated that 22 subjects were sufficient.

In conclusion, female recreational runners who had previously sustained ITBS exhibited a greater peak hip internal rotation and adduction angle for the injured limb compared to the matched limb of the control group. No differences in rearfoot or knee mechanics were observed

between the groups. These data may may explain how, overtime, atypical running mechanics can lead to lower extremity musculoskeletal injuries such as ITBS. However, prospective studies are necessary to better determine the role of gait mechanics and the development of running-related injuries.

ACKNOWLEDGEMENTS

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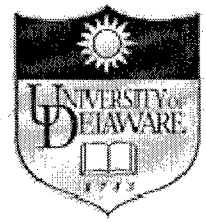
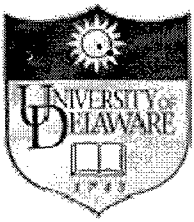
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Figure 1



Appendix 3
Advertisement Flyer



ATTENTION FEMALE **RUNNERS**



We are looking for Female Distance Runners who meet the criteria below to help better understand the mechanisms involved in Lower Extremity Running Injuries.



◆ Female runners are at a higher risk of sustaining a lower extremity running injury than males.

◆ Make a significant contribution to this area of research and gain a better understanding of your own lower extremity structure.

Inclusion Criteria:

- **Ages 18-30**
- **Run at least 20 miles per week**

Requirements: One two-hour data collection at the University of Delaware in Newark that includes a lower extremity evaluation by a licensed physical therapist and 3-D motion capture of your running gait. You will be compensated for your time.

Please contact Brian Noehren at 302-831-4646 or bnoehren@udel.edu

Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 milner@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu	Running Injury Study Brian Noehren 831-4646 bnoehren@udel.edu
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Appendix 4

Curriculum Vitae for Irene S. McClay

Irene S. Davis
Curriculum Vitae

PERSONAL

Address: 305 McKinly Lab, University of Delaware, Newark, DE 19716
Phone: (H): (302) 234-0532 (O): (302) 831-4263, (fax): (302) 831-4234
Email: mcclay@udel.edu www.udel.edu/pt/davis/index.htm
SSN: 047-40-3391

EDUCATION

PhD	1990	Pennsylvania State University	Biomechanics
MEd	1984	University of Virginia	Biomechanics
BS	1978	University of Florida	Physical Therapy
BS	1977	University of Mass.	Exercise Science

EMPLOYMENT

Director of Research, Drayer Physical Therapy Institute, (9/04 - present)

Development of research within the Joyner Sportsmedicine Institute aimed at advancing the science of sportsmedicine and improving prevention, diagnosis and treatment of orthopedic and sports-related injuries.

Director of Research, Joyner Sportsmedicine Institute, (6/97 - 8/04)

Development of research within the Joyner Sportsmedicine Institute aimed at advancing the science of sportsmedicine and improving prevention, diagnosis and treatment of sports-related injuries.

Associate Professor, Program in Physical Therapy, University of Delaware. (5/97 - present)

Assistant Professor, Program in Physical Therapy, University of Delaware. (9/89 - 5/97)

Instruction of graduate students in physical therapy. Research in biomechanics with specific interest in lower extremity mechanics and injury. Director, Running Injury Clinic.

Research Assistant, Pennsylvania State University, Center for Locomotion Studies. (8/85 - 6/89)

Responsible for the development and coordination of the Running Injury Clinic and Orthopedic Clinic. Research activities in locomotor biomechanics. Consultant to the Distance Runner's Camp at US Olympic Training Center.

Research and Teaching Assistant, University of Virginia, Rehabilitation Engineering Center. (8/82-8/85)

Research activities in wheelchair ergonomics. Instructor of graduate courses in biomechanics and human dissection. Co-coordinator of the Arts and Science of Sports Medicine Conference held annually at the University of Virginia (6/84, 6/85)

Physical Therapist, Blue Ridge Rehabilitation Associates, Charlottesville, VA (1/83 - 7/85)
Part time home health and private practice physical therapy.

Physical Therapist, Woodrow Wilson Rehabilitation Center, Fishersville, VA (2/79 - 6/82)
Patient treatment, supervision of physical therapy students, inservice training and
Coordinator of the Amputee Clinic. Instructor in continuing education course in
Management of the Spinal Cord Injured Patient.

Grants

Gait Retraining to Reduce Loading in Runners (in review). R01 submitted to the
National Institutes of Health for **\$1.50 million** for 4 years.

Real-time Gait Retraining to Reduce Loading in Runners (in review). R01
submitted to the National Institutes of Health for **\$1.70 million** for 4 years.

The Use of an Instrumented Treadmill to Alter Locomotor Patterns. Army
Research Office for \$230,000 for one year beginning 09/01/05

Gait Retraining in Runners through Realtime Feedback (in review). R01
submitted to the National Institutes of Health (NIAMS) for **\$453,000** for 3 yrs.

The Effect of Wedged Foot Orthoses on Lower Extremity Mechanics and
Function in Patients with Knee Osteoarthritis. National Institutes of Health (COBRE
Grant) **\$932,815** for 5 years beginning 02/2002.

A Comparison of Custom and Semicustom Foot Orthotic Devices on Lower
Extremity Mechanics and Comfort in High and Low Arched Runners. The Pauline
Marshall Research and Education Foundation, **\$22,000** for one year grant period
beginning 2/2004 .

A Comparison of Custom and Semicustom Foot Orthotic Devices on Lower
Extremity Mechanics and Comfort. The Pauline Marshall Research and Education
Foundation, **\$15,000** for one year grant period beginning 9/2001 .

Biomechanical Factors Associated with the Etiology of Stress Fractures in Runners. The
Department of the Army. **\$1.05 million** for 5 yr grant period beginning 9/2000.

2 Doctoral Scholarship. **\$20,000**. Joyner Sportsmedicine Institute, 1998, 1999, 2000, 2001;
\$36,000 for 2002. 2003

Undergraduate Summer Scholarship. **\$4,000**. Joyner Sportsmedicine Institute, 1997 and
1998, 1999, 2000, 2001

A Comparison of Four Methods to Obtain a Negative Impression of the Foot, **\$3,250**, Foot
Management, Inc, 1998-1999

The Effect of Different Orthotic Devices on Lower Extremity Mechanics of Rearfoot and
Forefoot Strikers, **\$3,500**. Foot Management, Inc, 1999-2000.

- The Effect of the Protonics System on Patellar Alignment and Gait in Patients with Patellofemoral Joint Pain. **\$18,000**. Funded by Inverse Technology, 1998-1999
- Clinical Efficacy of the Protonics System in Patients with Patellofemoral Joint Pain. **\$3,000**. Funded by Inverse Technology, 1998-1999
- A Comparison of Strengthening vs. Orthotics on Pronation and Pronation Velocity. Funded by the Physical Therapy Foundation **\$60,000**, 1993-1995
- Lower Extremity Mechanics and Injury. Funded by the Whitaker Foundation **\$180,000**, 1993-1996.
- The Relationship between Subtalar Joint Axis Orientation, Joint Motion and Injuries in Runners. Funded by the Biomedical Research Support Grant. **\$2550**, 1992
- The Relationship between Subtalar Joint and Knee Joint Motion in Runners. Funded by the University of Delaware Research Foundation. **\$16,000**, 1990.
- A Comparison of Patellofemoral 3-D Kinematics in Runners with and without Patellofemoral Pain. Doctoral Dissertation. Foundation for Physical Therapy. **\$8500**, 1988.

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In Review

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- Dierks, T and McClay Davis, I** (2004). Discrete and continuous joint coupling measures in recreational runners. (in review) *Clinical biomechanics*
- Deleo, A, Dierks, McClay Davis, I** (2004) A comparison of semi-custom and custom orthoses on rearfoot control and comfort. (in review) *J. Ortho. Sports PT*
- Davis, I, Milner, C, Williams, D, & Manal, K.** (2004) A comparison of lower extremity mechanics between runners with rearfoot and forefoot strike patterns. (in review) *Med Sci Sport and Exercise*
- Zifchock, RA, Davis, IS, Hillstrom, H, & Song, Jinsup** (2005). The effect of age, gender and lateral dominance on arch height and stiffness. (in review). *Foot and Ankle, Intl*
- Zifchock, RA, Davis, IS. & Hamill, J.** (2005) Kinetic asymmetry in female runners with and without tibial stress fractures (in review) *Journal of Biomechanics*
- Milner, CE, Davis, ID, Ferber, R, Pollard, CD & Hamill, J** (2005). Biomechanical factors associated with tibial stress fractures in female runners. (in review) *Med Sci Sport and Exercise*
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Abstracts

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Willson, JD and Davis, IS. **Clinical quantification of frontal plane knee angle: Correlation of 2D and 3D motion analysis.** Presented at the American Society of Biomechanics Mtg, Portland, OR, September 2004.

Dierks, TA, Davis, IS, and Hamill, J. Lower Extremity Joint Coupling in Runners who Develop Patellofemoral Pain Syndrome. Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.

Milner, CE, Davis, IS And Hamill, J. Does Sustaining a Lower Extremity Stress Fracture alter Lower Extremity Mechanics in Runners? Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.

Butler, RJ, Davis, IS, Royer, T, Crenshaw, S and Mika, ES. Differences in Frontal Plane Mechanics during Walking between Patients with Medial and Lateral Knee Presented at the American American Society of Biomechanics Mtg, Portland, OR, September 2004.

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Dierks, T. and Davis, I (2004). "Lower extremity joint coupling and patellofemoral pain during running." Presented at the American College of Sportsmedicine Meeting, Indianapolis, IA, June, 2004.

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Zifchock, RA, Davis, IS & Butler, RJ. Arch Height Differences between Genders and across Decades. Presented at the annual CBER Research Day, University of Del., May, 2004

- Milner, CE, **Davis, IS** And Hamill, J. Does Sustaining a Lower Extremity Stress Fracture alter Lower Extremity Mechanics in Runners? Presented at the annual CBER Research Day, University of Del., May, 2004
- Dierks, TA & Davis, IS. "Lower Extremity Joint Coupling and Patellofemoral Joint Pain in Runners" Presented at the annual CBER Research Day, University of Del., May, 2004
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- Dierks, TA, **McClay Davis, I**, and Ferber, R. Gender differences in discrete joint coupling variables during running. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- DeLeo, AT, Ferber, R, Mika, ES and **McClay Davis, I**. Comparison of rearfoot motion and comfort between custom and semi-custom orthotics based on arch height. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Butler, RJ, Ferber, R and **McClay Davis, I**. Gender differences in lower extremity stiffness during running. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Pollard, CD, Maclean, C, **McClay Davis, I** and Hamill, J. Knee joint kinematics during a single limb squat: Gender based differences in the collegiate soccer player. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- Ferber, R, **McClay Davis, I**, Hamill, J and Pollard, CD. Prospective biomechanical investigation of Iliotibial band syndrome in competitive female runners. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
- McClay Davis, I**, Dierks, TA and Ferber, R. Gender differences in continuous joint coupling variables during running. Presented at the American College of Sports Medicine Mtg, San Francisco, CA, May 2003
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- DeLeo, A, **McClay Davis, I** and Ferber, R. Custom and Semi-custom orthotic devices: A comparison of motion control and comfort. Presented at the World Congress of Biomechanics Mtg, Calgary, Canada, August, 2002.
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- Pollard CD, **McClay IS**, Hamill J. Multiple Lower Extremity Stress Fractures in a Female Division I Cross-Country Runner: A Case Study. Presented at the Combined Sections Meeting of the APTA, Boston, MA, February 2002.
- McCrory, JL, Quick NE, Ballantyne, BT, and **McClay Davis, I**. Effects of a Dynamic Knee Orthosis on Subject Kinematics during the Lateral Step-Up Exercise. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.
- Ferber, R, **McClay Davis, I**, Hamill, J,, Pollard, CD, and McKeown, KA. Kinetic Variables in Subjects with Previous Lower Extremity Stress Fractures. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.
- Pollard, CD, McKeown, KA, Ferber, R, **McClay Davis, I** and Hamill, J. Selected Structural Characteristics of Female Runners with and without Lower Extremity Stress Fractures. Presented at the American College of Sports Medicine Meeting in St. Louis, MO, June, 2002.

- Leetun, DT, Ireland, ML, Ballantyne, BT and **McClay, IS**. Differences in Core Stability between Male and Female Collegiate Basketball Athletes as Measured by Trunk and Hip Performance. Presented at the ACL Research Retreat, Lexington, KY, April, 2001
- Ireland, ML, Ballantyne, BT, Little, K and **McClay, IS**. A Radiographic Analysis of the Relationship between the Size and Shape of the Intercondylar Notch and Anterior Cruciate Ligament Injury Presented at the ACL Research Retreat, Lexington, KY, April, 2001
- Shapiro, R, Yates, J, **McClay, I**, and Ireland, ML. Male-Female Biomechanical Differences in Selected Landing Maneuvers. Presented at the ACL Research Retreat, Lexington, KY, April, 2001
- Laughton, CA, **McClay, IS**, Hamill, J Effect of Orthotic Intervention and Strike Pattern on Tibial Shock in Runners. Presented at the International Society of Biomechanics, Zurich, Switzerland, July, 2001
- McClay, IS**, Hughes, MA, Laughton, CA, Gupta, R. Effect of Soft Orthotics on Tibial Shock and Rearfoot Motion. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Manal, KT & **McClay, IS** Errors in Estimating Tibial Translation during Natural Cadence Walking: Bone vs. Skin Mounted Tracking Markers. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Laughton, CA, **McClay, IS**, & J. Hamill. Effect of Foot Orthoses and Strike Pattern on Rearfoot Motion. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Ballantyne, BT, Leetun, D, Ireland, ML, & **McClay, IS**. Gender differences in core stability as measured by trunk and hip performance Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- McCrory, JL, Quick, NE, Ballantyne, BT & **McClay, IS**. Effect of a Resistive Dynamic Knee Orthosis on Muscle Activations During the Lateral Step Up. Presented at the American College of Sports Medicine Mtg, Baltimore, June, 2001.
- Laughton, CA and **McClay, IS**. Relationship between Loading Rates and Tibial Accelerometry in Forefoot Strike Runners. Presented at the Annual American Society of Biomechanics Mtg, Chicago, IL, July, 2000
- Williams, DS and **McClay, IS**. Lower Extremity Stiffness in Runners with High and Low Arches. Presented at the Annual American Society of Biomechanics Mtg, Chicago, IL, July, 2000.
- Manal, KT, **McClay, IS**, Richards, J and Stanhope, SJ. Effect of Marker Placement on Knee Joint Moments. Presented at the Canadian Society of Biomechanics Mtg, Montreal, July, 2000.
- Hamill, J, Heidersheidt, B, **McClay, IS**, Li, L. Influence of Strike Pattern on Lower Extremity Stiffness in Runners. Presented at the Canadian Society of Biomechanics Mtg, Montreal, July, 2000.
- Williams, DS and **McClay, IS**. Injury Patterns in Runners with Pes Cavus and Pes Planus. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.

Sahte, V, Ireland, ML, Ballantyne BT and **McClay, IS**. Acute Effect of the Protonics System on Patellofemoral Alignment. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.

Ott, S, Ireland, ML, Ballantyne, BT and **McClay, IS**. Gender Differences in Functional Outcomes following ACL Reconstruction. Presented at the ACSM National Mtg in Indianapolis, IN, June, 2000.

Williams, DS, **McClay, IS** & Laughton, CA. A Comparison of between day Reliability of Different Types of Lower Extremity Kinematic Variables in Runners. Presented at the American Society of Biomechanics, October, 1999, Pittsburgh, PA.

McClay, IS, Williams, DS & Laughton, CA. Can Gait be Retrained to Prevent Injury in Runners? Presented at the American Society of Biomechanics, October, 1999, Pittsburgh, PA.

McClay, IS, Williams, DS and Baitch, S. The Effect of the Inverted Orthotic on Lower Extremity Mechanics. Presented at the International Society of Biomechanics Mtg, August, 1999, Calgary, Canada

McClay, IS, & Williams, DS. Structure and Mechanics of Injured Twin Runners. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.

Wills, J & **McClay, IS**. Epidemiology of Extreme Sports. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.

Crook, S, Ballantyne, BT & **McClay, IS**. Reliability of a Functional Assessment Tool. Presented at the ACSM National Mtg in Seattle, WA, June, 1999.

Laughton, CA, **McClay, IS** and Williams, DS. A Comparison of Methods of Obtaining a Negative Impression of the Foot. Presented at the National APTA Conference, Washington, DC, June, 1999.

Williams, DS, **McClay, IS**. Reliability and Validity of Arch Characterizing Measurements. Presented at the Combined Sections Mtg of the APTA, Seattle, WA, February, 1999.

McClay, IS, Williams, DS, and Manal, KT. Lower Extremity Mechanics of Runners with a Converted Forefoot Strike Pattern. NACOB, Chicago, IL, 1998

Manal, KT, **McClay, IS** et al. A Comparison of Surface Mounted Markers and Attachment Methods in estimating Tibial Rotations during Walking. Am. Soc. Biom. Mtg, Clemson, SC, Oct, 1997

McClay, IS The Relationship between Lower Extremity Mechanics and Injury in Runners to be presented at the Whitaker Conference, Utah, August, 1996.

McClay, IS & Manal, KT A Comparison of Rearfoot and Knee Kinematics during Running between Excessive Pronators and Normals. Presented at the Canadian Orthopedic Research Society Meeting, Quebec City, May, 1996.

McClay, IS & Manal, KT Lower Extremity Kinematic Comparisons between Forefoot and Rearfoot Strikers. Presented at the American Society of Biomechanics Meeting, Stanford, CA August, 1995.

McClay, IS & Manal, KT Lower Extremity Kinetic Comparisons between Forefoot and Rearfoot Strikers. Presented at the American Society of Biomechanics Meeting, Stanford, CA August, 1995.

- McClay, IS & Manal, KT** Coupling Parameters in Runners who Pronate and Normals. Presented at the American Society of Biomechanics Meeting, Columbus, Ohio, November, 1994.
- McClay, IS & Manal, KT** (1995). A Comparison of Two- and Three-dimensional Lower Extremity Kinematics during Running between Pronators and Normals. (Presented at the American Society of Biomechanics Meeting, Columbus, Ohio, November, 1994.
- McClay, IS, Cavanagh, PR, Sommer, HJ, & Kalenak, A:** "Three-Dimensional Kinematics of the Patellofemoral Joint during Running". Proceedings of the American Society of Biomechanics Meeting, October, 1991, Tempe, AZ.
- McClay, IS, Cavanagh, PR, Sommer, HJ, & Kalenak, A:** "The Effect of Orthotic Treatment on Tibiofemoral and Patellofemoral Joint Kinematics". *Physical Therapy*, 71(6):S46-7, 1991.
- McClay, IS, Cavanagh, PR, Sommer, HJ, Woltring, HJ, & Kalenak, A:** "Three-Dimensional Angular Kinematics of the Tibiofemoral Joint During Running". Proceedings of the International Symposium on 3-D Analysis of Human Movement, Montreal, July, 1991.
- Cavanagh, PR, Robinson, JR & McClay, IS:** "Biomechanical Perspective of Stress Fractures in Professional Basketball Players". *Med Sci Sport and Exercise* 22:(2) S104, April, 1990.
- Woltring, HJ, McClay, IS, & Cavanagh, PR:** "3-D Photogrammetric Camera Calibration without a Calibration Object." Abstract published in the Proceedings of the International Society of Biomechanics Meeting, Los Angeles, CA, June, 1989.
- McClay, IS, Cavanagh, PR, & Kalenak, A:** "Biomechanical Evaluation of the Injured Runner" Abstract published in the Proceedings of the East Coast Gait Conference, November, 1987.
- Brubaker, CE, McClay, IS, & McLaurin, CA:** "Effect of Seat Position of Propulsion Efficiency." Proceedings of the 2nd International Conference on Rehabilitation Engineering, 1984, pp. 134-138.
- Brubaker, CE, McClay, IS, & McLaurin, CA:** "The Effect of Mechanical Advantage on Lever Propulsion Efficiency". Proceedings of the 6th Annual Conference on Rehabilitation Technology, 1983, pp. 122-124.

SELECTED INVITED PRESENTATIONS

- Davis, IS.** "Stress Fractures: Study of Relationship between Mechanics and Injury" Presentation given at the Australian Institute for Sport, Canberra, Australia, February 2005.
- Davis, IS.** "Foot Structure, Mechanics and Injury Risk" Keynote Presentation at the 2nd International Foot and Ankle Symposium, Newark, DE, October 2004.
- Davis, IS.** "The Effect of Laterally Wedged Foot Orthoses on Lower Extremity Mechanics of Patients with Medial Knee OA". Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Boston, MA, October, 2004.
- Davis, IS.** "Is there a right way to run? Relationships between mechanics and injury" Presented at the and Science of Sports Medicine, Charlottesville, VA, June, 2004.

- Ireland, ML, Davis, IS, and Willson, J "The influence of lumbopelvic strength on lower extremity performance." Presented at the International ACL Study Group Mtg, Sardinia, Italy, June, 2004
- Davis, IS. "Relationships between structure and mechanics" Presented at the and Science of Sports Medicine, Charlottesville, VA, June, 2004.
- Davis, IS & Hamill, J. "The Biomechanical Etiology of Stress Fractures in Female Runners. Presented at the United States Army Research Institute of Environmental Medicine", May, 2004.
- Davis, IS. "Influence of Foot Biomechanics on Overuse Injuries of the Knee" Presented in the "Mechanisms of Knee Injuries: Implications for Prevention and Rehabilitation" Symposium. Combined Sections Mtg of the APTA, Nashville, TN, February, 2004
- Davis, IS. "Is there a right way to run? Relationships between mechanics and injury" Presented at the Graduate Research Symposium, Penn State University, January, 2004,
- Davis, IS "A Research Update on Orthotic Intervention" Presented at the Research Symposium at the Temple University College of Podiatric Medicine, December, 2003
- Davis, IS "Foot and ankle case studies in runners" Presented at the Research Symposium at the Temple University College of Podiatric Medicine, December, 2003
- Davis, IS "Is there a right way to run? Relationships between mechanics and injury" Presented at the National Congress of Sports Medicine in Stavanger, Norway, November, 2003.
- Davis, IS "The Role of Core Stability in Lower Extremity Injuries" Presented at the University of MA seminar series, Amherst, MA, November, 2003.
- Davis, IS "Comparison of Comfort and Rearfoot Control between a Semicustom and Custom Foot Orthoses" Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Las Vegas, NV, December 2003.
- Davis, IS "Biomechanical Considerations for Various Types of Foot Orthoses" Presented in the minisymposium titled "Clinical and Biomechanical Efficacy of Foot Orthoses" at the American College of Sports Medicine Mtg in San Francisco, CA, May, 2003.
- Davis, IS "Influence of Foot and Ankle Mechanics of Patellofemoral Joint Dysfunction: A Ground Up Biomechanical Perspective. Presented in the minisymposium titled "The Influence of Lower Quarter Mechanics on Patellofemoral Joint Dysfunction" at the American College of Sports Medicine Mtg in San Francisco, CA, May, 2003.
- Davis, IS "Case Studies in the Injured Runner" Presented at the Medical Aspects of Sports Medicine Mtg, University of Delaware, March, 2003.
- Davis, IS "Evidence for the Effect of Foot Orthoses on Lower Extremity Mechanics" Presented at Temple University College of Podiatric Medicine. February, 2003
- Davis, IS "The Relationship between Structure and Function in the Foot and Ankle". Presented at the Foot Management Inc. Mtg, Ocean City, MD, October 2002
- Davis, IS "Normal and Abnormal Gait" Presented at the Foot Management Inc. Mtg, Ocean City, MD, October 2002

- Davis, IS "The Effect of the Inverted Orthotic on Lower Extremity Mechanics in Patients with Patellofemoral Joint Pain. Presented at the Prescription Foot Orthotic Laboratory of America (PFOLA) Mtg, Montreal, Canada, October 2002.
- Davis, IS "Structural Deformities of the Foot: Assessment and Clinical Implications" Presented at the National Athletic Trainers Association Mtg, Dallas, TX, June, 2002
- Davis, IS "Running Mechanics and Injury" Presented at the National Athletic Trainers Association Mtg, Dallas, TX, June, 2002
- Davis, IS "The Role of Core Instability in Lower Extremity Injuries" Symposium: ACL Injuries and the Gender Bias. Presented at the American College of Sports Medicine Mtg in St. Louis, May, 2002.
- Davis, IS "Biomechanical Case Studies in Running Injuries" Symposium: Evidence for injury mechanisms in runners. Presented at the American College of Sports Medicine Mtg in St. Louis, May, 2002.
- " Davis, IS "The Application of Biomechanics to Sports Medicine: Focus on Running Injuries" **Keynote lecture** at the Midwest Student Biomechanics Symposium, Normal, IL, March, 2002.
- Davis, IS "Core Instability and Lower Extremity Mechanics: Implications for Injury." Presented at the Combined Sections Meeting of the APTA, Boston, MA, February, 2002.
- Davis, IS "An Update on the Mechanics behind the Success of Orthotic Intervention" Presented at Temple University School of Podiatric Medicine research seminar series, Philadelphia, PA, February 2002.
- Davis, IS "An Update on Orthotic Research: What do Orthotics do?" Presented at the Biokinesiology Graduate Research Seminar Series at the University of Southern California, Los Angeles, CA, November, 2001.
- Davis, IS "The Effect of the Inverted Orthotic on Lower Extremity Mechanics: An Update" Presented at the Prescription Foot Orthotic Laboratory Association Annual Meeting, Miami, FL, November, 2001
- Davis, IS "How Do Foot Orthotic Devices Influence Lower Extremity Mechanics. Presented at the Prescription Foot Orthotic Laboratory Association Annual Meeting, Miami, FL, November, 2001
- McClay, IS "Selected Case Studies in Running Injuries" Presented at the Combined Sections Meeting of the APTA, San Antonio, TX, Feb, 2001.
- McClay, IS "Developing Standards in Epidemiological Research" Presented at the National ACSM Mtg in Indianapolis, June, 2000
- McClay, IS "Lower Extremity Mechanics and Injury Patterns in High and Low Arch Runners". Keynote lecture presented at the Foot and Ankle Research Retreat, Annapolis, MD, May, 2000
- McClay, IS "Effect of the Inverted Orthotic on Rearfoot and Knee Mechanics" Presented at the 4th Annual John Weed Seminar, Palm Springs, CA, March, 2000 and the PFOLA meeting in Vancouver, BC, November 2000
- McClay, IS "Influence of foot, knee and hip coupling on patellofemoral mechanics" Symposium at the Combined Sections Meeting of the APTA, New Orleans, LA, February, 2000 and at the National ACSM Mtg in Indianapolis, June, 2000, and the Arts and Science of Sports Medicine, Charlottesville, VA, June, 2000.

- McClay, IS "Visual Gait Analysis in Runners" Presented at the Arts and Science of Sports Medicine, Charlottesville, VA, June, 2000.
- McClay, IS "Injury Mechanisms in Runners" Keynote speaker at the Fifth IOC Congress on Sport Sciences, Sydney, Australia, November, 1999
- McClay, IS "Clinical Gait Analysis" Keynote speaker at the Fifth IOC Congress on Sport Sciences, Sydney, Australia, November, 1999.
- McClay, IS "Risk Factors in Anterior Cruciate Ligament Injuries" Clinical Colloquium presented at the National ACSM Mtg, in Seattle, WA, June, 1999
- McClay, IS "Problem Solving the Injured Runner" Clinical Colloquium presented at the National ACSM Mtg, in Seattle, WA, June, 1999
- McClay, IS "Coupling between the Foot and the Knee in Runners" Presented at Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, October, 1999
- McClay, IS "Biomechanics of the Knee" Presented at Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, October, 1999
- McClay, IS "Physical Therapist to Marathoner - A Classical Tale of Overuse." Presented at the Case Conference Seminar at the Annual Conference of the American Physical Therapy Association, Minneapolis, MN, June, 1998
- McClay, IS Eugene Michels Research Forum - "Instrumented versus Visual Gait Analysis in Clinical Assessments" Presented at the Combined Sections Mtg in Dallas, TX, Feb., 1997
- McClay, IS "Biomechanical Differences between Forefoot and Rearfoot Strikers" presented at the Joyner Sportsmedicine Institute National Conference, Hilton Head, SC, Nov. 1996.
- McClay, IS "Plantar Fasciitis: A Case Study" Presented at the Case Conference Seminar at the Annual Conference of the American Physical Therapy Association, Minneapolis, MN, June, 1996.
- McClay, IS "The Use of Motion Analysis in Physical Therapy". University of PA, Philadelphia, October, 1995.
- McClay, IS "The Patellofemoral Joint - Implications of the study of three-dimensional kinematics". Grand Rounds, Dept. of Orthopedic Surgery, Hershey Medical Center, January, 1995.
- McClay, IS "What is Clinical Research". Keynote Address at Research Symposium, Shenandoah University, April, 1994 .
- McClay, IS "Research in Foot and Ankle Biomechanics". Presented at the Combined Sections Meeting of the American Physical Therapy Association, New Orleans, LA, February, 1994
- McClay, IS "Biomechanical Assessment of Gait" Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1993
- McClay, IS "Closed Kinetic Chain Activities for the Foot and Ankle" Presented at the Foot and Ankle Seminar for HealthSouth in Orlando, FL, February, 1993, Phoenix, AZ, March, 1993, St. Louis, MO, April, 1993 and for Foot Mgt, Inc in Ocean City, MD in October, 1994 and April, 1996.
- McClay, IS "Normal Structure and Gait". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1992, and at the Symposium on the Biomechanics of the Lower Extremity, NATA, Denver, CO, February, 1992.

- McClay, IS "Abnormal Structure and Gait". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1992, and at the Symposium on the Biomechanics of the Lower Extremity, NATA, Denver, CO, February, 1992 and for Foot Mgt, Inc in Ocean City, MD in October, 1994 and April, 1996.
- McClay, IS "The Biomechanical Evaluation of the Injured Runner". Presented at the Medical Symposium of the Penn Relays, April, 1992, The Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1998 and the East Coast Gait Conference, Bethesda, Md, November, 1997
- McClay, IS "Biomechanics of the Foot and Ankle". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1991
- McClay, IS "Relationship between Mechanics and Running Injuries". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1991.
- McClay, IS "Anatomy and Biomechanics of the Patellofemoral Joint". Presented at the Sports Physical Therapy Meeting, Orlando, Fla. December, 1990
- McClay, IS "Relationship between Structure and Function in Patellofemoral Disorders". Presented at the Sports Physical Therapy Meeting, Orlando, Fla. December, 1990
- McClay, IS "Normal and Abnormal Running Mechanics". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va. June, 1990
- McClay, IS "Biomechanical Perspective of Stress Fractures in Professional Basketball Players". Presented at the Annual Meeting of the NBA Physicians, West Palm Beach, FL, November, 1988.
- McClay, IS "The Biomechanics of Patellofemoral Disorders". Presented at the Arts and Science of Sports Medicine Conference, Charlottesville, Va., June, 1988.
- McClay, IS "Biomechanical Profile of Elite Woman Distance Runners". Presented at the Dogwood Festival Pre-race Conference, Atlanta, GA, July, 1988.

CONTINUING EDUCATION

- Biomechanics of the Foot and Ankle. 2 day course sponsored by Drayer Physical Therapy Institute, Hummelstown, PA, February, 2004
- Biomechanics of the Foot and Ankle. 2 day course sponsored by NovaCare Physical Therapy, Chicago, IL, January, 2004
- Biomechanics of the Foot and Ankle. 2 day course sponsored by NovaCare Physical Therapy, Raleigh, NC, September, 2003
- Biomechanics of the Foot and Ankle. 2 day course sponsored by NovaCare Physical Therapy, Alexandria, VA November, 2003
- Biomechanic and Orthotic Treatment of the Foot and Ankle - 2 day course sponsored by Joyner Sportsmedicine Institute, Harrisburg, PA, March, 2001
- Foot and Ankle Biomechanics and Orthotic Therapy. 2 day course sponsored by NovaCare Physical Therapy, Philadelphia March, 2000
- Course on Orthotics. 2 day course presented to Foot Management, Inc, Ocean City, MD October, 2002

The Lower Kinetic Chain. 2 day course sponsored by Foot Management, Inc, Ocean City,
MD October, 1998

HONORS

Fellow, American College of Sports Medicine	2001
Summa Cum Laude Graduate, The Penn State University	1990
Physical Therapy Foundation Scholar	1988
Recipient of Zipser Scholarship, The Penn State University	1988
Outstanding Masters Student Award, University of Virginia	1984
Nominee for Mary McMillan Scholarship Award, APTA	1978
Magna Cum Laude Graduate, University of Florida	1978
Magna Cum Laude Graduate, University of Massachusetts	1977

PROFESSIONAL ACTIVITIES

Societies	American Society of Biomechanics Abstract reviewer, Annual ASB Mtg, Chicago, IL, July 2000 Membership Committee (1997-2001) Scientific Committee for the Third International Symposium on 3-D Analysis of Human Movement, Stockholm, Sweden, 1994 American College of Sports Medicine, Fellow American Physical Therapy Association (APTA) Orthopedic and Research Sections Member Chairperson of Research Committee of the Foot and Ankle Special Interest Group (1997-present) International Society of Biomechanics
Advisory	Medical Consultant for Runners World (1995-present)
Ed. Board	Clinical Biomechanics (1999-present) Journal of Orthopedic and Sports Physical Therapy (1996-1997) Journal of Applied Biomechanics (1997-1999)
Reviewer	Journal of Biomechanics Medicine and Science in Sports and Exercise Foot and Ankle, International Journal of the American Podiatric Medical Association Journal of Applied Biomechanics
NIH panels	Invited Participant to the "Working Conference on Gait Analysis in Rehabilitation Medicine" National Institutes for Health, September, 1996 NIH study section on Musculoskeletal Modeling, Chaired by Peter Cavanagh, November, 2003
Other	Organizing Chair for Research Retreat – Measurement of Foot Motion: Forward and Inverse Dynamic Models, University of Southern California, Los Angeles, CA, April, 2004 Organizing Chair for Research Retreat - ACL Injuries: The Gender Bias. Lexington, KY, April 2001, 2003, 2006

Organizing Chair for Research Retreat - Static and Dynamic Classification of the Foot.
Annapolis, MD, May, 2000.

Member, Organizing Committee, Joyner Sportsmedicine Institute National Sportsmedicine
Conference, Hilton Head, SC (1996-1999)

Doctoral Research Advisory Committee (grant reviews), American Physical Therapy
Association (1995-1997)

Licensure Licensed Physical Therapist, State of Delaware

Appendix 5

Curriculum Vitae for Joseph Hamill

Last updated: 6/7/2005

CURRICULUM VITAE

Joseph Hamill

Professor and Chair, Department of Exercise Science
Associate Dean, School of Public Health and Health Sciences
University of Massachusetts Amherst
and
Professor, Neuroscience and Behavior Program
University of Massachusetts Amherst

BUSINESS ADDRESS: Biomechanics Laboratory
Department of Exercise Science
University of Massachusetts
Amherst, MA 01003
(413) 545-2245
(413) 545-2906 Fax
jhamill@excsci.umass.edu

PERSONAL DATA: Date of Birth: 3/3/46
Height: 5' 9"
Weight: 180 lbs
Citizenship: U.S.

EDUCATION

1967	Teaching Certificate	Lakeshore Teacher's College, Toronto, Canada
1972	B.A.	York University, Toronto, Canada
1977	B.S. (magna cum laude)	Concordia University, Montreal, Canada
1978	M.S.	University of Oregon, Eugene, Oregon
1981	Ph.D.	University of Oregon, Eugene, Oregon

Undergraduate Areas of Study: Political Science
General Science

Graduate Area of Study: Biomechanics

RESEARCH INTERESTS

Mechanics of lower extremity function
Mechanical Analysis of normal and pathological gait.
Modeling the lower extremity in gait.
Optimality criteria in human locomotion
Dynamical Systems

EMPLOYMENT EXPERIENCE

1981-1982	Post-doctoral Fellow Biomechanics Laboratory, University of Oregon
1982-1985	Assistant. Professor (Biomechanics) Department of Physical Education, Southern Illinois University
1985-1986	Assistant Professor (Biomechanics) and Graduate Program Director Department of Physical Education, Southern Illinois University
1986-1988	Assistant Professor (Biomechanics) Department of Exercise Science, University of Massachusetts
1989-1995	Associate Professor (Biomechanics) and Graduate Program Director Department of Exercise Science, University of Massachusetts
1990-1995	Adjunct Professor Department of Medicine, University of Massachusetts Medical Center
1995-1996	Associate Professor (Biomechanics) and Department Chair Department of Exercise Science, University of Massachusetts
1996-	Professor (Biomechanics) and Department Chair Department of Exercise Science, University of Massachusetts
2003-	Professor and Associate Dean School of Public Health and Health Sciences, University of Massachusetts

RESPONSIBILITIES OF PRESENT POSITION

Associate Dean for Undergraduate Programs, School of Public Health and Health Sciences
Department Chair, Exercise Science
Director of the Biomechanics Laboratory
Teach graduate and undergraduate courses in Biomechanics
Advise undergraduate and graduate students

Chair graduate theses and dissertations in the Department
Conduct research in the area of Biomechanics
Secure external funding for the Biomechanics Laboratory

TEACHING RESPONSIBILITIES

Undergraduate

Ex Sc 300	Writing Seminar for Exercise Science
Ex Sc 305	Kinesiology
Ex Sc 304	Human Anatomy
Ex Sc 311	Anatomy of Human Motion
Ex Sc 474	Measurement and Evaluation Theory

Graduate

Ex Sc 531	Mechanical Analysis of Human Motion
Ex Sc 611	Introduction to Research
Ex Sc 732	Advanced Biomechanics
Ex Sc 892	Doctoral Seminar
Ex Sc 895	Clinical Biomechanics Seminar

UNIVERSITY SERVICE

Department Committees

Master's Thesis Review Committee, 1982-1983
Comprehensive Examination Review Committee, 1983-1984
Chair, Graduate Faculty, 1982-1986
Chair, Search Committee for Department Chairperson, 1986
Graduate Committee, 1986-
Telecommunications Committee, 1988-1990
Chair, Department Personnel Committee, 1994-1995
Chair, Motor Control Search Committee, 1994-1995
School Curriculum Committee, 2003-

College Committees

College Computer Advisory Committee, 1982-1986
School Personnel Committee, 1994-1995
School Executive Committee, 1995-
Member, School Development Officer Search Committee, 1997.

University Committees

Graduate Council, 1991
Recruitment and Retention Committee, 1991-92
Research Council, 1992-1995
Life Sciences Institute Advisory Council, 2003-
Undergraduate Deans Council, 2003-

PROFESSIONAL ORGANIZATIONS

American Alliance for Health, Physical Education, Recreation and Dance
Biomechanics Academy of the Research Consortium
International Society of Biomechanics
Canadian Society of Biomechanics
American Society of Biomechanics
American College of Sports Medicine
New England College of Sports Medicine
International Society of Biomechanics in Sport
ASTM
Association of Schools of Public Health

RESEARCH AFFILIATIONS

Scientific Advisory Board, Rockport Walking Institute, 1986-1992.
Scientific Advisory Board, LifeFitness, Inc., 1993-2004.
Scientific Advisory Board, USA Field Hockey, 1995-1998
USA Volleyball Sports Medicine and Performance Commission's Resource Advisory Committee, 1996-1999

ACADEMIC HONORS

Fellow, Research Consortium of the AAHPERD, 1984
Fellow, American College of Sports Medicine, 1986
Fellow, American Academy of Kinesiology and Physical Education, 1997
Award, Ruth Glassow Honor Award, Biomechanics Academy of NASPE, 2004

OFFICES IN PROFESSIONAL ORGANIZATIONS

1. Chair-elect, Kinesiology Academy, 1990-91.
2. Board Member, International Society of Biomechanics in Sports, 1992-94.
3. Chair, Biomechanics Interest Group of the American College of Sports Medicine, 1996-97.
4. Member-at-large, Executive Committee of the New England Chapter of the American College of Sports Medicine, 1995-1997.
5. Board Member, International Society of Biomechanics Technical Group on Footwear, 1998-2000.
6. Member, Credentials Committee, American College of Sports Medicine, 2000-2003.
7. Member-at-Large, Executive Board of Canadian Society of Biomechanics, 2000-2004
8. Member, Executive Board of the International Society of Biomechanics, 2003-

PROFESSIONAL SERVICE

Review Committees For Professional Meetings

1. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1989.
2. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1990.
3. Program Committee, combined meeting of the 9th International Symposium on Biomechanics in Sports and the Kinesiology Academy, June 29 - July 7, 1991.
4. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1991.
5. Review Panel Chair for Research Consortium, AAHPERD Convention, 1991-92.
6. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1992.
7. Review Panel Chair for Research Consortium, AAHPERD Convention, 1992-93.
8. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1993.
9. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1994.
10. Scientific Committee, International Society of Biomechanics in Sports Annual Meeting, Budapest, Hungary, June 1-6, 1994.
11. Abstract Review Committee, American College of Sports Medicine Annual Meeting, 1995.
12. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Madiera, Portugal, 1995-96.
13. Program Committee, New England American College of Sports Medicine Annual Meeting, Providence, RI, 1999.
14. Program Committee, New England American College of Sports Medicine Annual Meeting, Providence, RI, 2000.
15. Abstract Reviewer, XVIIIth Congress of the International Society of Biomechanics, ETH Zurich, Switzerland, July, 2001.
16. Abstract Reviewer, Vth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, July, 2001.
17. Member, Research Consortium Research Writing Award Committee, 2001.
18. Member, Holyoke Community College Department of Health and Fitness Advisory Board, 2001-
19. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Caceres, Spain, 2002.
20. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Beijing, China, 2003.
21. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Ottawa, Canada, 2004.
22. Abstract Reviewer, American College of Sports Medicine Annual Meeting, 2004.
23. Abstract Reviewer, American College of Sports Medicine Annual Meeting, 2005.
23. Abstract Reviewer, VIIth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, August, 2005.
24. Member, Organizing Committee, VIIth Symposium of the Footwear Working Group Symposium of the International Society of Biomechanics, August, 2005.
25. Abstract Reviewer, XXth Congress of the International Society of Biomechanics, Cleveland, OH, USA, August, 2005.
26. Member, Scientific Review Committee, International Society of Biomechanics in Sports Annual Meeting, Beijing, China, 2005.

External Reviewer for Theses and Dissertations

1. External Dissertation Reviewer, McMaster University, Hamilton, Ontario, Canada, June, 1995.
2. External Thesis Reviewer, Lakehead University, Thunder Bay, Ontario, Canada, June, 1995.
3. External Dissertation Reviewer, University of Guelph, Guelph, Ontario, Canada, January, 1997.
4. External Dissertation Reviewer, University of Connecticut, Storrs, Connecticut, December, 1998.
5. External Dissertation Reviewer, University of Delaware, Newark, Delaware, March, 2000.
6. External Thesis Reviewer, University of Delaware, Newark, Delaware, November, 2000.
7. External Dissertation Reviewer, University of Calgary, Calgary, Alberta, Canada, November, 2002.
8. External Dissertation Reviewer, Auckland University of Technology, Auckland, New Zealand, June, 2004.
9. External Dissertation Reviewer, University of Edinburgh, Edinburgh, Scotland, December, 2004.
10. External Dissertation Reviewer, University of Western Australia, Perth, Australia, March, 2005.
11. External Dissertation Reviewer, University of Delaware, Newark, Delaware, May, 2005.
12. External Dissertation Reviewer, Sheffield Hallam University, Sheffield, England, May, 2005.

External Grant Reviewer

1. External Reviewer for internal grants at University of Texas at Tyler, 1991.
2. Grant Reviewer, Natural Sciences and Engineering Council of Canada, 1993.
3. External Grant Reviewer, University Grants Committee, Hong Kong, February, 1998.
4. External Grant Reviewer, Natural Sciences and Engineering Council of Canada, May, 2000.
5. External Grant Reviewer, Canadian Institutes of Health Research, April, 2003.
6. External Grant Reviewer, USARIEM, Natick, MA, May, 2004.
7. External Grant Reviewer, Canadian Institutes of Health Research, April, 2004.
8. Grant Reviewer, Natural Sciences and Engineering Council of Canada, December, 2004.

Committee Member

1. Biomechanics Model Research Laboratory, Olympic Scientific Congress, University of Oregon, July, 1984.
2. Completed Research in Health, Physical Education, Recreation and Dance, 1986.
3. Research Consortium Program Review Committee, AAHPERD Annual Convention, April, 1987.
4. Kinesiology Academy, Nominating Board for Officers, 1987.
5. Completed Research in Health, Physical Education, Recreation and Dance, 1988.
6. Nominating Committee for Kinesiology Academy Chair, 1991.
7. Delegate to American Alliance Assembly, January 1, 1991 to December 31, 1991.
8. ASTM Committee F-8 on Sports Equipment and Facilities, June, 1992.

9. Conference Chair, International Society of Biomechanics in Sport Annual Meeting, University of Massachusetts Amherst, June 23-26, 1993.
10. Doctoral Program Evaluation Committee, American Academy of Kinesiology and Physical Education, 1997.
11. Program Review Committee for Biomechanics, Michigan State University, East Lansing, MI, January, 2000.
12. Continuing Committee for Doctoral Program Review, American Academy of Kinesiology and Physical Education, 2001-2002
13. Member, Research Consortium Research Writing Award Committee, 2001.
14. Member, AAHPERD Grant Proposal Committee, 2001.
15. Member, Holyoke Community College Department of Health and Fitness Advisory Board, 2001-
16. Coordinator, Grant Program of the Research Consortium, 2004-.

EDITORIAL BOARD OF PROFESSIONAL JOURNALS

Member, Editorial Review Board, *Pediatric Exercise Science*, 1988-
 Member, Editorial Review Board, *Medicine, Exercise, Nutrition, and Health*, 1991-1995
 Guest Editor, Special Issue of *Pediatric Exercise Science*, The Physically Challenged Child, May, 1992.
 Section Editor, Biomechanics, *Research Quarterly for Exercise and Sport*, 1993-96
 Member, Editorial Review Board, *Journal of Applied Biomechanics*, 1996-1999
 Member, Editorial Board, *Research Quarterly for Exercise and Sport*, 1998-1999
 Associate Editor, *Medicine and Science in Sports and Exercise*, 2000-2002
 Member, Editorial Review Board, *Sports Biomechanics*, 2000-
 Member, Editorial Review Board, *Journal of Sports Sciences*, 2001-
 Member, Editorial Review Board, *Exercise and Sports Science Review*, 2005-

AD HOC REVIEWER FOR PROFESSIONAL JOURNALS

Reviewer, *Medicine and Science in Sports and Exercise*, 1985-
 Reviewer, *International Journal of Sports Biomechanics*, 1986-
 Reviewer, *Research Quarterly for Exercise and Sport*, 1989-
 Reviewer, *Sports Medicine*, 1991-
 Reviewer, *Journal of Gerontology*, 1991-
 Reviewer, *Journal of Orthopedic and Sports Physical Therapy*, 1991-
 Reviewer, *Journal of Applied Biomechanics*, 1993-
 Reviewer, *Journal of Applied Physiology*, 1993-
 Reviewer, *Journal of Biomechanics*, 1993-
 Reviewer, *Clinical Journal of Sports Medicine*, 1996-
 Reviewer, *British Journal of Sports Medicine*, 1996-
 Reviewer, *Clinical Biomechanics*, 1999-
 Reviewer, *Exercise and Sports Science Review*, 2000-
 Reviewer, *European Journal of Applied Physiology*, 2000-
 Reviewer, *Journal of Rehabilitation Research and Development*, 2002-

PUBLICATIONS

Osternig, L. R., Sawhill, J. A., Bates, B. T., **Hamill, J.** A method for rapid collection and processing of isokinetic data. *Research Quarterly for Exercise and Sport* 53(3):252-257, 1982.

Knutzen, K. M., Bates, B. T., **Hamill, J.** Electrogoniometry of post surgical knee bracing in running. *American Journal of Physical Medicine* 62(4):172-181, 1983.

Osternig, L. R., **Hamill, J.**, Sawhill, J. A., Bates, B. T. Influence of torque and joint speed on power production. *American Journal of Physical Medicine* 62(4): 163-171, 1983.

Hamill, J., Bates, B. T., Sawhill, J. A., Knutzen, K. M. Variations in ground reaction force parameters at different running speeds. *Human Movement Sciences* 2:47-56, 1983.

Hamill, J., Bates, B. T., Knutzen, K. M. Ground reaction force symmetry during walking and running. *Research Quarterly for Exercise and Sport* 55(3):289-293, 1984.

Knutzen, K. M., Bates, B. T., **Hamill, J.** Knee brace influences on the tibial rotation and torque patterns of the surgical limb. *Journal of Orthopaedic and Sports Physical Therapy* 6(2):116-122, 1984.

Osternig, L. R., **Hamill, J.**, Corcos, D. M., Lander, J. E. Electromyographic patterns accompanying isokinetic exercise under varying speed and sequencing conditions. *American Journal of Physical Medicine* 63(6):289-297, 1984.

Knutzen, K. M., **Hamill, J.**, Bates, B. T. Ambulatory characteristics of the visually disabled. *Human Movement Sciences* 4:55-66, 1985.

Lander, J. E., Bates, B. T., Sawhill, J. A., **Hamill, J.** A comparison between free-weight and isokinetic bench pressing. *Medicine and Science in Sports and Exercise* 17(3): 344-353, 1985.

Smith, P. K., **Hamill, J.** The effect of punching glove type and skill level on momentum transfer. *Human Movement Studies* 12(3):153-161, 1986.

Hamill, J., Knutzen, K. M., Bates, B. T., Kirkpatrick, G. M. Evaluation of two ankle appliances using ground reaction force data. *Journal of Orthopaedic and Sports Physical Therapy* 7(5):244-249, 1986.

Osternig, L. R., **Hamill, J.**, Lander, J. E., Robertson, R. Coactivation of sprinter and distance runner agonist/antagonist muscles in isokinetic exercise. *Medicine and Science in Sports and Exercise* 18(4):431-435, 1986.

Hamill, J., Ricard, M. D., Golden, D. M. Angular momentum in multiple rotation non-twisting platform dives. *International Journal of Sport Biomechanics* 2(2): 78-87, 1986.

Knutzen, K. M., Bates, B. T., Schot, P., **Hamill, J.** Knee brace evaluation. *Medicine and Science in Sports and Exercise* 19(3):303-309, 1987.

Hamill, J., Murphy, M. V., Sussman, D. H. The effects of track turns on lower extremity function. *International Journal of Sport Biomechanics* 3(3):276-286, 1987.

Hamill, J., Morin, G., Clarkson, P. M., Andres, R. O. Exercise moderation of foot function during walking with a re-usable semirigid ankle orthosis. *Clinical Biomechanics* 3(3):153-158, 1988.

Hamill, J., Bates, B. T. A kinetic evaluation of the effects of in vivo loading on running shoes. *Journal of Orthopaedic and Sports Physical Therapy* 10(2):47-53, 1988.

Hamill, J., Freedson, P. S., Boda, W., Reichsman, F. Effects of shoe type and cardiorespiratory responses and rearfoot motion during treadmill running. *Medicine and Science in Sports and Exercise* 20(5):515-521, 1988.

Greer, N. L., **Hamill, J.**, Campbell, K. R. Ground reaction forces in children's gait. *Pediatric Exercise Science* 1(1):45-53, 1989.

Hamill, J., Knutzen, K. M., Bates, B. T., Kirkpatrick, G. M. Relationship of static and dynamic measures of the lower extremity. *Clinical Biomechanics* 4(4):217-225, 1989.

Greer, N. L., **Hamill, J.**, Campbell, K. R. Dynamics of children's gait. *Human Movement Sciences* 8:465-480, 1989.

Brown, D. B., Knowlton, R. G., **Hamill, J.**, Schneider, T. L., Hetzler, R. K. Physiological and biomechanical differences between wheelchair-dependent and able-bodied subjects during wheelchair ergometry. *European Journal of Applied Physiology* 60:179-182, 1990.

Holt, K. G., **Hamill, J.**, Andres, R. O. The force driven harmonic oscillator as a model for human locomotion. *Human Movement Science* 9:55-68, 1990.

Hamill, J., McNiven, S. L. Reliability of ground reaction force parameters during walking. *Human Movement Science* 9:117-131, 1990.

Robertson, R. N., Osternig, L. R., **Hamill, J.**, DeVita, P. EMG-torque relationships during isokinetic dynamometer exercise. *Sports Training, Medicine and Rehabilitation* 2:1-10, 1990.

Holt, K. G., **Hamill, J.**, Andres, R. O. Predicting the minimal energy cost of human walking. *Medicine and Science in Sports and Exercise* 23(4):491-498, 1991.

Hamill, J., Freedson, P. S., Clarkson, P. M., Braun, B. Muscle soreness during running: biomechanical and physiological implications. *International Journal of Sports Biomechanics* 7(2):125-137, 1991.

Devita, P., Hong, D. M., **Hamill, J.** Effects of asymmetric load carrying on the biomechanics of walking. *Journal of Biomechanics* 24(12):1119-1129, 1991.

Ebbeling, C. J., **Hamill, J.**, Freedson, P. S., Rowland, T. W. Efficiency in Children's Gait. *Pediatric Exercise Science*. 4(1):36-49, 1992.

Widrick, J., Freedson, P. S., **Hamill, J.** Effect of internal work on the calculation of optimal pedalling rates. *Medicine and Science in Sports and Exercise* 24(3): 376-382, 1992.

Hamill, J., Bates, B. T., Holt, K. G. Timing of lower extremity joint actions during treadmill running. *Medicine and Science in Sports and Exercise* 24(7):807-813 1992.

Foti, T., Ebbeling, C. J., **Hamill, J.**, Ward, A., Rippe, J. Stair climbing machines: Lower extremity kinematics and exercise intensity comparisons. *Medicine, Exercise, Nutrition, and Health* 2:162-169, 1993.

Ebbeling, C. J., **Hamill, J.**, Crusemeyer, J. A. Lower extremity mechanics and the energy cost of walking in high-heeled shoes. *Journal of Orthopaedic and Sports Physical Therapy* 19 (4):190-196, 1994.

Holt, K. G., Jeng, S. F., Ratcliffe, R., **Hamill, J.** Energetic cost and stability during human walking at the preferred stride frequency. *Journal of Motor Behavior* 27(2): 164-178, 1994.

Hamill, J., Derrick, T. R., Holt, K. G. Shock attenuation and stride frequency during running. *Human Movement Science* 14:45-60, 1995.

Whittlesey, S. N., **Hamill, J.** An alternative model of the lower extremity during locomotion. *Journal of Applied Biomechanics* 12(2):269-279, 1996.

Jensen, R. L., Freedson, P. S., **Hamill, J.** The prediction of power and efficiency during near-maximal rowing. *European Journal of Applied Physiology* 73:98-104, 1996.

Hamill, J., Caldwell, G. E., Derrick, T. R. Reconstructing digital signals using Shannon's Sampling Theorem. *Journal of Applied Biomechanics* 13:226-238, 1997.

Mahar, A. T., Derrick, T. R., **Hamill, J.**, Caldwell, G. E. Impact shock and attenuation during in-line skating. *Medicine and Science in Sports and Exercise* 29(8):1069-1075, 1997.

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Ebbeling, C. J., **Hamill, J.,** Foti, T., Ward, A., Rippe, J. Kinematics of the lower extremity on stair-stepping machines. New England Chapter of the American College of Sports Medicine Annual Meeting, Marlborough, MA, November, 1990.

Hintermeister, R. A., **Hamill, J.** Is symmetry valid in running? New England Chapter of the American College of Sports Medicine Annual Meeting, Marlborough, MA, November, 1990.

Boda, W. L., **Hamill, J.** Kinematic variations in three different backward presses in springboard diving. New England Chapter of the American College of Sports Medicine Annual Meeting, Marlborough, MA, November, 1990.

Elliott, E. H., **Hamill, J.**, Derrick, T. R. Reliability of the LiftStation measurement system. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1993.

Derrick, T. R., **Hamill, J.**, Foti, T. Spectral analysis of EMG during running in orthotic/non-orthotic conditions. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1993.

Elliott, E. H., **Hamill, J.**, Derrick, T. R. The influence of multiple lifts on load kinematics in males and females. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1994.

Mahar, A., **Hamill, J.**, Derrick, T. R. Impact attenuation during running. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1994.

Li, L., Swanson, S. C., Caldwell, G. E., **Hamill, J.** Measurement of lower extremity stiffness during the stance phase of level and downhill walking. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1995.

Swanson, S. C., Derrick, T. R., **Hamill, J.** Impact attenuation and forefoot stiffness in hiking boots. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1995.

Hardin, E. C., **Hamill, J.**, Taylor, J. M. The influence of midsole durometer on leg shock, hemocrit and muscle damage during downhill running. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1995.

Heiderscheit, B. C., **Hamill, J.**, Derrick, T. R. Relationship between Q-angle and lower extremity kinematics during running. Annual Conference of the Massachusetts Chapter of the APTA, Danvers, MA, October, 1996.

Busconi, K., Gore, M., **Hamill, J.**, Freedson, P. Time motion profile of U. S. Olympic field hockey players during game conditions. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1996.

Heiderscheit, B. C., **Hamill, J.**, Derrick, T. R. Relationships between Q-angle and lower extremity kinematics. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November, 1996.

Goff, D., **Hamill, J.**, Clarkson, P. Biomechanical and biochemical changes after downhill running. New England Chapter of the American College of Sports Medicine Annual Meeting, Providence, RI, September, 1997.

KEYNOTE PRESENTATIONS

Mechanics of tower dive take-offs. United States Diving Association Annual Convention, Phoenix, AR, September, 1985.

Mechanics of walking. National Prescription Footwear Association, New York, NY, November, 1987.

Athletic Footwear and Injury. American Public Health Annual Meeting, Boston, Massachusetts, November 15, 1988.

Biomechanics of the lower extremity. Southeast Chapter of the American College of Sports Medicine Annual Meeting, Louisville, Kentucky, February 2, 1991.

Timing of lower extremity joint actions: A mechanism for knee injury? Northwest Chapter of the American College of Sports Medicine Annual Meeting, Eugene, OR, February 11, 1993.

Running injuries and rehabilitation. International Society of Biomechanics in Sports Annual Meeting, Budapest, Hungary, June 5, 1994.

Biomechanical aspects of children during exercise. IXth Annual NASPEM Conference, Pittsburg, PA, August 12, 1994.

Evaluation of athletic footwear using ground reaction force data. International Society of Biomechanics in Sports Annual Meeting, Madiera, Portugal, June, 1996.

Biomechanics of distance running. International Symposium of the Research Institute of Sports Science at Korean National University, Seoul, Korea, October 17, 1997.

Evaluation of shock attenuation. Fourth Symposium of the Technical Group on Footwear Biomechanics, Canmore, Alberta, Canada, August 6, 1999.

Segment coupling and running injuries. University of Nevada-Las Vegas Distinguished Lecture Series, Las Vegas, Nevada, March 1, 2002.

Role of variability in the etiology of lower extremity running injuries. International Symposium of the Research Institute of Sports Science at Korean National University, Seoul, Korea, October 25, 2002.

Has biomechanics influenced footwear design and development? Staffordshire Conference on Clinical Biomechanics, Stoke on Trent, UK, April 23, 2004.

The Biomechanics of Athletic Footwear. Southern California Conference on Biomechanics, California State University Fullerton, Fullerton, California, April 23, 2005.

INVITED PRESENTATIONS

Effects of running shoes on foot function. Y.M.C.A., Eugene, OR, October, 1981.

Medio-lateral foot function during locomotion. University of Illinois Graduate Faculty and students, Champaign, IL, February, 1983.

Biomechanics of walking. American Heart Association Walk for Life, St. Louis, MO, May, 1987.

Biomechanics of walking and running shoes. New Mexico Race Walkers Association, Albuquerque, New Mexico, June, 1987.

Biomechanics of fitness walking. American Diabetes Association, St. Louis, Missouri, September, 1987.

Orthotics and lower extremity function. Athletic Training Symposium, American Alliance for Health, Physical Education, Recreation and Dance Annual Meeting, Kansas City, Missouri, April, 1988.

Running analysis from both a biomechanical and physiological perspective. Symposium, New England College of Sports Medicine Annual Meeting, Worcester, MA, November 4, 1988.

If the shoe fits: A biomechanical analysis of locomotion. Sigma Xi Society, University of Massachusetts, Amherst, MA, November 16, 1988.

Muscle soreness during running: Biomechanical and physiological considerations. Neuromuscular Research Center Seminar, Boston University, September 20, 1989.

Design of athletic shoes : Biomechanical considerations. Kinesiology Academy Meeting at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, New Orleans, LA, April 28, 1990.

Biomechanical implications of the design of running shoes. Physical Therapy Department, Boston University, April 18, 1990.

Biomechanics of running. Physical Therapy Department, Boston University, November 6, 1990.

Is biomechanics an atheoretical discipline? Kinesiology Academy Teaching Conference, Ames, Iowa, July 5, 1991.

Biomechanics of Running. Education Resources Inc. Conference, Framingham, MA, September 27, 1991.

Optimality criteria for human locomotion. Motor Control/Biomechanics Seminar, Department of Exercise and Human Movement Studies, University of Oregon, January, 1992.

Biomechanical considerations for equipment design in children's sports. Seminar on Children's Activities, United Hospital Medical Center, Port Chester, NY, March 28, 1992.

Efficiency of children's gait. (with C. J. Ebbeling). Kinesiology Academy Symposium at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, Indianapolis, IN, April 13, 1992.

Optimality criteria for human locomotion. (with K. G. Holt and A.F. Maliszewski). Symposium at the American College of Sports Medicine Annual Meeting, Seattle, Washington, June 5, 1993.

The influence of step aerobics on knee angle. Research Symposium at the IDEA Annual Conference, New Orleans, Louisiana, June 21, 1993.

Rearfoot motion in running. (with K. G. Holt and C. J. Edington). Symposium at the New England College of Sports Medicine Annual Meeting, Boxborough, MA, November 5, 1993.

Controversies in the calculation of mechanical energy. (with K. D. Browder and L. Darby). Biomechanics Academy Symposium at the American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, Denver, CO, April 13, 1994.

Stability and rearfoot motion testing: A proposed standard. (with M. Milliron and J. Healy). VIIIth Biennial Meeting of the Canadian Society for Biomechanics, Calgary, Canada, August, 1994.

Stride Frequency and Foot Strike Impact. Dept. of Exercise and Sports Science. Arizona State University, December 8, 1994.

Biomechanics of functional footwear. (with M. Shorten). Pre-Conference Symposium at the International Society of Biomechanics Biannual Meeting, Jyvaskyla, Finland, June, 1995.

Impact shock attenuation during conditions of altered stride frequencies in running. (with T. R. Derrick and K. G. Holt). Biomedical Engineering Society Meeting, Boston, MA, October, 1995.

Shoe and surface influences on ACL injuries. (with B. Busconi). American Volleyball Coaches Annual Meeting, Springfield, MA, December 15, 1995.

A force-driven harmonic oscillator model of human locomotion. German Sports University, Cologne, Germany, February 29, 1996.

If the shoe fits: the biomechanics of running shoes. American Medical Athletic Association, Boston, MA, April 12, 1996.

Biomechanics of athletic footwear. (with Martyn Shorten). American Alliance of Health, Physical Education, Recreation, and Dance Annual Meeting, Atlanta, GA, April, 1996.

An oscillator model of locomotion. University of Massachusetts Physics Department Seminar, Amherst, MA, May 1, 1996.

The mechanics of orthotics. New England Chapter of the American College of Sports Medicine Annual Meeting, Boxborough, MA, November 7, 1996.

A case study of a patient with patellofemoral pain. Eugene Michaels Lecture at the Combined Sections Meeting of the American Physical Therapy Association Annual Meeting, Dallas, Texas, February 14, 1997.

Oscillator Models of Human Locomotion. Korean Sports Science Institute, Seoul, Korea, October 15, 1997.

Lower extremity variability during running. Physical Therapy Department Seminar, University of Delaware, February 20, 1998.

Shock attenuation and transmission during running. (with T. R. Derrick). XVIIth Congress of the International Society of Biomechanics, Calgary, Alberta, Canada, August 12, 1999.

Variability and Stability: A Dynamical Systems Perspective. (with Van Emmerik, R. E. A., Heiderscheit, B., Li, L). Invited Symposium at the Annual Meeting of the American College of Sports Medicine, Indianapolis, IN, June, 2000.

From a Pendulum to a Spring. Department of Kinesiology, Louisiana State University, Baton Rouge, LA, October 24, 2000.

Oscillators and Springs. The Gladys Garrett Honor Lecture, Department of Exercise Science, University of Connecticut, Storrs, CT, May, 2001.

Joint Coupling variability and knee pain during running. (with B. Heiderscheit, R. Van Emmerik, J. Haddad). XVIIIth Congress of the International Society of Biomechanics, ETH Zurich, Switzerland, July, 2001.

Current Issues in Biomechanics. Beijing University, China, October 16, 2001.

Mechanical models and human locomotion. Beijing University, China, October 18, 2001.

A primer in 3-D: Considerations for biomechanical research. University of Las Vegas-Nevada, Las Vegas, Nevada, February 28, 2002.

Tibial stress fractures: A prospective study. Human Performance Laboratory, University of Calgary, Calgary, Alberta, Canada, November 29, 2002.

Is There a Gender Bias in Anterior Cruciate Ligament Injuries? Departments of Physical Therapy and Exercise and Sports Science, East Carolina University, Greenville, NC, October 16, 2003.

Future Direction in Biomechanics Doctoral Education. Biomechanics Academy, New Orleans, Louisiana, April 2, 2004.

Footwear in athletics. University of Staffordshire Graduate Seminar, Stoke on Trent, UK, April 21, 2004.

The Gender Bias in Anterior Cruciate Injuries. Seventh International Conference on Foot Biomechanics and Orthotic Therapy, Boston, MA October 29, 2004.

Is there a Gender Bias in Lower Extremity Injuries? Department of Sports Science, University of Edinburgh, Edinburgh, Scotland, December, 2004.

Biomechanics, Exercise Physiology and the 75th Anniversary of the Research Quarterly for Exercise and Sports, American Alliance of Health, Physical Education, Recreation and Dance Annual meeting, Chicago, IL, April 19, 2005.

EXTERNAL FUNDING

Grants

1. Dynamics of platform diving, United States Diving Association, \$3,000, 1/1984 - 12/1984. 9/1985 - 6/1986.
2. Effects of anatomically variant foot-types on walking gait, ORDA, Southern Illinois University, \$6,000,
3. Effect of orthotic inserts on walkers with rearfoot and forefoot dysfunctions. Biomedical Research Support Grant, University of Massachusetts, \$6,000, 1/1987 - 1/1989.
4. Activity in later life: effects on posture and gait. National Institute of Aging, co-principal investigator, resubmitted January 28, 1988 (approved but not funded).
5. Musculoskeletal fitness norms for individuals aged 45-75. National Institute of Health, submitted February 1, 1988 (approved but not funded).
6. Mechanics of springboard diving: Modeling the diver-board system, United States Diving Association, \$15,000, 1/1989 - 1/1991.
7. Biomechanical analysis of military boots, (Grant #DAAK60-91-C-0102) U.S. Army, Natick, MA, \$183,000, 7/1991 - 12/1992.
8. Biomechanical analysis of military boots, (Grant #DAAK60-95-R-8010) U.S. Army, Natick, MA, (with Wellco Industries, North Carolina), \$51,436, 9/1995 - 12/1997.

9. Biomechanical analysis of military boots: Phase III, (Grant #DAAK60-95-R-8010) U.S. Army, Natick, MA, (with Wellco Industries, North Carolina), \$5,000, 9/1999 - 12/1999.
10. Biomechanical analysis of military boots. (Contract #DAAK16-00-P-0112) U.S. Army Soldier Systems Center, Natick, MA, \$25,000, 1/2000 - 6/2000.
11. Prospective study on tibial stress fractures. (Grant # DAMD17-00-1-0515), Department of the Army, (with Irene McClay). \$1,050,000, 8/1/2000 - 8/1/2004.

Contracts

1. Mechanics of lower extremity function, Isotechnologies, Inc., \$12,000, 9/1982 - 6/1984.
2. Ergonomics of lower extremity function, KangaROOS, USA, \$58,000, 9/1986 - 9/1989.
3. Prophylactic Knee and Ankle Bracing, AirCast Corp., \$20,000, 9/1988 - 9/1989.
4. Lower extremity action during exercise, Life-Fitness Group, \$6,000, 7/1990 - 7/1992.
5. Lower extremity mechanics, Hyde Athletic Shoe Company, \$279,000, 1/1989 - 1/1997.
6. Biomechanical analysis of golf equipment, Titleist and FootJoy Worldwide, \$283,000, 6/1992-12/1997.
7. Biomechanical analysis of hiking gait, The Timberland Company, \$15,000, 3/1995 - 10/1995.
8. A physiological profile of the game of field hockey. (with P. S. Freedson). United States Olympic Committee, Colorado Springs, Colorado, \$35,132, 1/1996 - 12/1996.
9. Locomotor patterns on running machines. NordicTrak, \$10,000, 9/1997-3/1998.
10. Plantar pressure patterns during hiking gait. The Timberland Company, \$42,000, 3/1998 - 5/1999.
11. Investigation of foot scaling using a 3-D laser measurement system. Titleist and FootJoy Worldwide, \$50,000, 1/1999 - 12/2000
12. Biomechanical analysis of golf footwear, Titleist and FootJoy Worldwide, \$63,000, 1/1999-12/1999.
13. Walking and running mechanics and their effect on footwear, Hyde Athletic Shoe Company, \$33,000, 1/1999 - 12/1999.

14. In-shoe temperatures during hiking, The Timberland Company, \$15,000,
1/1999-3/1999.
15. Plantar forces during basketball movements, And1 Company, \$15,000,
1/1999-3/1999.
16. Rearfoot motion and shock attenuation in trial running footwear, The
Timberland Company, \$10,000, 6/1999-7/1999.
17. Running mechanics and their effect on footwear. Hyde Athletic Shoe
Company, \$33,000, 1/2000 - 12/2000.
18. Implementation of a 3-D laser measurement system. Titleist and FootJoy
Worldwide, \$89,000, 1/2000 - 12/2000.
19. Shock attenuation in hiking footwear. The Timberland Company, \$18,000,
1/2000 - 6/2000.
20. Traction analysis of golf footwear. Titleist and FootJoy Worldwide, \$48,000,
1/2000 - 12/2000.
21. Prospective study on tibial stress fractures. (with Irene McClay). US Army, \$1,050,000,
8/1/2000 - 8/1/2004.
22. Footwear Testing. Titleist and FootJoy Worldwide. \$50,000, 1/2001 -
12/2001.
23. 3-D laser measurement system. Titleist and FootJoy Worldwide, \$89,000,
1/2001 - 12/2001.
24. Walking mechanics and their effect on footwear. Hyde Athletic Shoe
Company, \$33,000, 1/2001 - 12/2001.
25. Modeling Parachute Landing Falls. Sub-contract from Foster-Miller, Inc.,
Waltham, MA, \$85,000, 1/2001 - 8/2003.
26. A new 3-D laser measurement system. Titleist and FootJoy Worldwide,
\$69,000, 1/2002 -

12/2002.

- 12/2002.
27. Footwear Testing. Titleist and FootJoy Worldwide, \$50,000, 1/2002 -
28. Footwear Testing. Hyde Athletic Shoe Company, \$16,500, 1/2002 - 6/2002.
29. Footwear Testing, Timberland Company, \$24,000, 1/2002 – 12/2002.
- 12/2003.
30. Footwear Testing. Titleist and FootJoy Worldwide, \$124,000, 1/2003 -
31. Footwear Testing, Timberland Company, \$24,000, 1/2003 – 12/2003.
32. Footwear Testing. Acushnet Company, \$60,000, 1/2004 - 12/2004.
33. Footwear Testing. Acushnet Company, \$60,000, 1/2005 - 12/2005.